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Report

on the

UTILIZATION OF THE EXTERNAL TANKS OF THE

SPACE TRANSPORTATION SYSTEM

A Workshop held at the
University of California, San Diego
La Jolla, California
August 23-27, 1982

Hosted by the California Space Institute,
Scripps Institution of Oceanography
Sponsored by NASA Contract #NAS 8-35037
from the Marshall Space Flight Center

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*Specific recommendations are given in each section.

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UTILIZATION OF THE EXTERNAL TANKS OF THE

SPACE TRANSPORTATION SYSTEM

I. INTRODUCTION

This is the report of a study group which met in La Jolla, California, August 23-27, 1982, to examine possible uses of the Shuttle External Tank in orbit, especially uses which might apply to a future space station. A list of participants is included in Appendix I.

This meeting, and the larger study of which it is a part, grew out of the interest of a NASA advisory committee -- headed by Dr. James Fletcher -- in relatively low-cost, incremental approaches to a space station. The External Tank is an obvious candidate for study in this connection.

We have no idea who first suggested carrying the ET into space for use as a long-duration facility; the idea may well date to the first days of Shuttle design. Some of us first heard it more than five years ago. Our group's first serious look at the possibilities was during a smaller meeting in La Jolla in March, 1982, which produced a report for Dr. Fletcher and NASA favoring more intense study of the possibilities. More ideas were developed soon after, and these were received well enough to elicit financial support from NASA Headquarters (through the Marshall Space Flight Center), for a year-long study of which the August meeting was an integral part. We have also received backing from aerospace companies, General Dynamics-Convair and Martin-Marietta. We hope to develop similar ties with other interested companies. We are also about to receive support from DARPA, in the Department of Defense.

We begin our report with a brief description of the External Tank (ET). Figure 2 offers an exploded view, Figure 3 an inadequate idea of scale. Table 1 gives some mass figures. (Figures 2 and 3, and Table 1 appear in the Viewgraph section.) The length -- 50 meters -- and diameter -- 8.4 meters -- make the Tank comparable in size to an 11-story building, such as Tioga Hall at UCSD, in which the study group met.

Present STS operations require the tank reenter the atmosphere following Main Engine Cutoff, prior to orbital insertion. The tank is torn apart by aerodynamic forces and the debris impact in the Indian Ocean (ETR-launches). Controlled ditching of the ET eliminates the risk of later uncontrolled reentry of an ET haphazardly left in orbit on its own.

Many engineers and scientists have contended that at least some of the ET's should be utilized in space. An ET in earth orbit has a greater mass than the averge STS payload. The tanks are very large, rugged, pressure vessels which might be useable directly. They could be modifiable to a wide range of uses without interfering with their main propellant tankage role. In addition, the ET's and their contained residuals might serve as a source of raw materials for a wide range of other manufactured products, devices or consumables in space.

The decisions which will be made about Space Station functions and structures cannot, of course, be foreseen at this time. However, we believe a few points are clear, and these form the bases of assumptions for our work. They are:

(1) The station or stations should be developed so as to permit staged or incremental growth.

(2) Some key functions of a space station can be compared to the concept of an automotive service station on earth: refueling, service and repair.

(3) The station must provide, or assist, capability of raising large payloads to Geosynchronous orbit, or putting them into other special orbits.

(4) In addition, there are major opportunities here to serve other constituencies, civilian and military.

In this report we address these issues, and discuss many ways in which the Shuttle External Tank could contribute dramatically to the future utilization of space.

We are of course aware that, as with other technologies, there are problems as well as opportunities, and that some issues will require study beyond our capability or charter. One problem, preventing uncontrolled return of tank or tank-based systems to the earth, is discussed in several places in our report (see Systems particularly). We believe there are attractive options. A potentially serious managerial concern, the growth in cost of an initially simple system as the project proceeds ("Christmas Tree Effect") is recognized; it exists to some degree in any low cost approach. The technical and historical issues involved in man-rating modified ET's are another challenge. Other concerns, such as the technology of adding propulsion, air locks, life support and other functions to a tank, and of assemblying tanks, plane and altitude changes, are dealt with in appropriate sections. We hope that tradeoff studies on space station altitude will be made elsewhere; we generally assume 500 km (270 nautical miles) for discussion purposes.

The report is organized in sections by topic as given in the Table of Contents. Each begins with an introduction (usually), the recommendations of the group responsible for that section. The text follows, usually with some key references. We would much appreciate comments, criticisms, and corrections. The editors responsible for each section are:

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*Area Code 714 changes to 619, November 6, 1982.

A. Major Recommendations

1. The U. S.-Italian tether satellite experiment should be flown as early as possible. Besides its own merit, it provides a first full test of tether technology.

2 An external tank should be put in space at the first reasonable opportunity. There are interesting options using such a tank in the 1980's, before the space station as such is launched.

3 Serious study of the ET, as a major component of an incrementally developed space station program, is timely and should begin now. This should include requirements for hardware modification, and an examination of a wide range of architectural options, and at least the range of potential applications covered in this report.

B. Viewgraphs

The following viewgraphs were presented September 2, 1982 at the Space Station Task Force Meeting in Washington, D. C.

KEY RECOMMENDATIONS OF AUGUST 23-27 MEETING

- FLY U.S.-ITALIAN TETHER SATELLITE EXPERIMENT A.S.A.P.
- ET OFFERS OPPORTUNITIES IN THE 1980's WITHIN THE PRESENT STS PROGRAM
- ET APPEARS TO OFFER A BROAD RANGE OF OPTIONS FOR AN INCREMENTALLY DEVELOPED SPACE STATION PROGRAM
- NASA SHOULD CONDUCT SERIOUS AND DETAILED STUDIES OF ET UTILIZATION. REQUIREMENTS FOR ET HARDWARE MODIFICATION SHOULD BE DEFINED. LOOK AT WIDE RANGE OF APPLICATIONS.

ISSUES AND PROBLEMS

- LIFETIME IN ORBIT
- PREVENTING COST GROWTH
- DEFINITION OF MAN-RATING
- TETHERS STILL UNTRIED

MILITARY APPLICATIONS OF THE ET

ET OFFERS:

- CONCEALMENT
- PRESSURE CAPABLE VOLUME
- SHIELDING
- BED PLATE IN ORBIT
- MOMENTUM
- MATERIALS, PARTS

MILITARY USES OF THESE INCLUDE:

- ON-ORBIT ASSET STORAGE
- TARGET PROLIFERATION
- SENSOR STORAGE/BASING
- SOURCE OF BALLISTIC MATERIALS
- DEEP SPACE TRANSPORT ELEMENT

TETHER PRIORITIES AND TASKS

1. FLY TETHERED SUBSATELLITE A.S.A.P. EXPLORE ITS TECHNOLOGY AS BASIS FOR ET APPLICATIONS.

2. PLAN STORAGE OF ONE OR MORE TETHERED ET'S IN ORBIT.

3. TETHER-RELATED ISSUES NEEDING EARLY STUDY:
   - (a) ENHANCEMENT OF SPACE STATION CAPABILITIES USING TETHERS
   - (b) TETHER MATERIALS AND HARDWARE FOR LONG-TERM USE
   - (c) ELECTRODYNAMICS OF TETHERS
   - (d) PROCEDURES FOR RENDEZVOUS CAPTURE OF ORBITING OBJECTS BY TETHERS
   - (e) PRECISE CONTROL OF EXCITATION AND DAMPING OF OSCILLATIONS
   - (f) VARIOUS DESIGN TRADEOFFS

4. CONSIDER TETHER-ET SYSTEMS FOR STS ENCHANCEMENT.

STAGES OF ET HARDWARE MODIFICATION AS NOW FORESEEN; IN APPROXIMATE ORDER

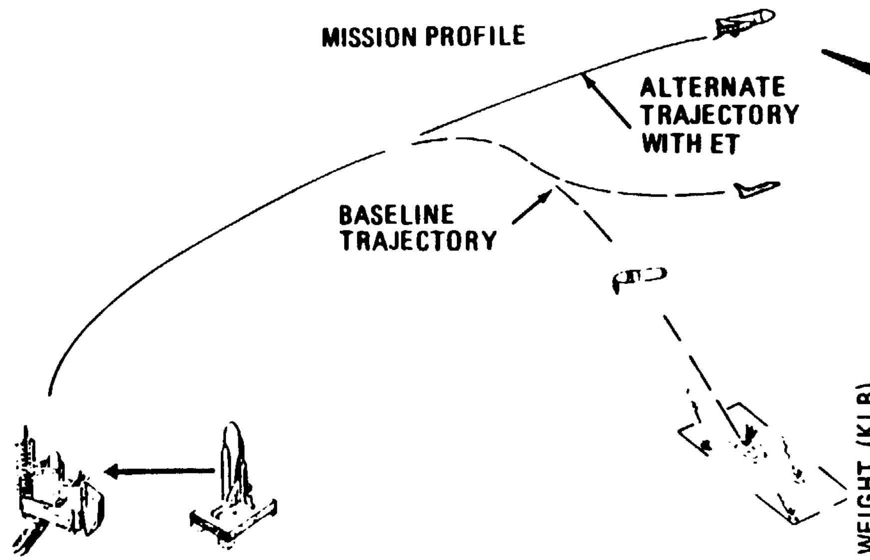
- TANK UNMODIFIED OR WITH TETHER ATTACHMENT
- PROPELLANT SCAVENGING
- 36" AIR LOCK ATTACHED TO PORT OR PORTS; SENSORS AND PERHAPS ATTITUDE CONTROL PACKAGE
- ENHANCED CARGO CAPABILITY -- ACC OR OTHER
- ORBIT BOOST/MAINTENANCE CAPABILITY
- JOINING HARDWARE FOR MULTIPLE TANK ASSEMBLY

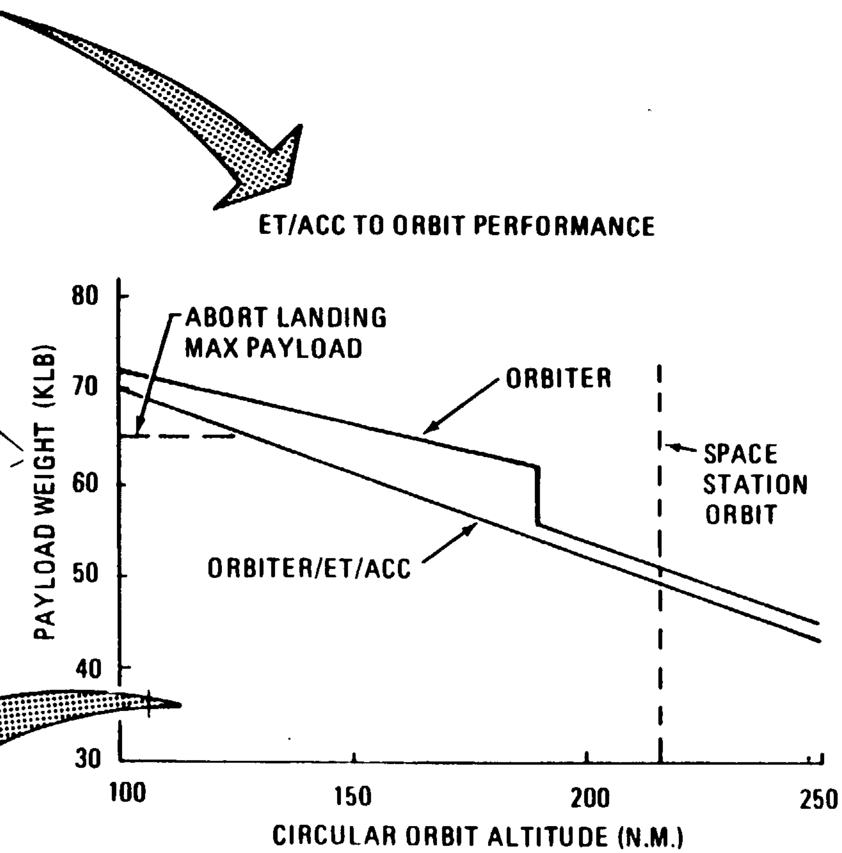
EXAMPLES OF POSSIBLE FIRST USES OF ET IN ORBIT

- PROOF OF CONCEPT -- TETHER
- LIFEBOAT
- ENHANCED CARGO CAPABILITY (ACC OR ALTERNATIVE)
- SCIENCE (OCCULTATION, ETC.)
- LONG DURATION EXPERIMENTS (BIOLOGY, COSMIC RAYS)
- MILITARY

FIGURE 1

THE ACC OFFERS MAJOR GROWTH AND FLEXIBILITY



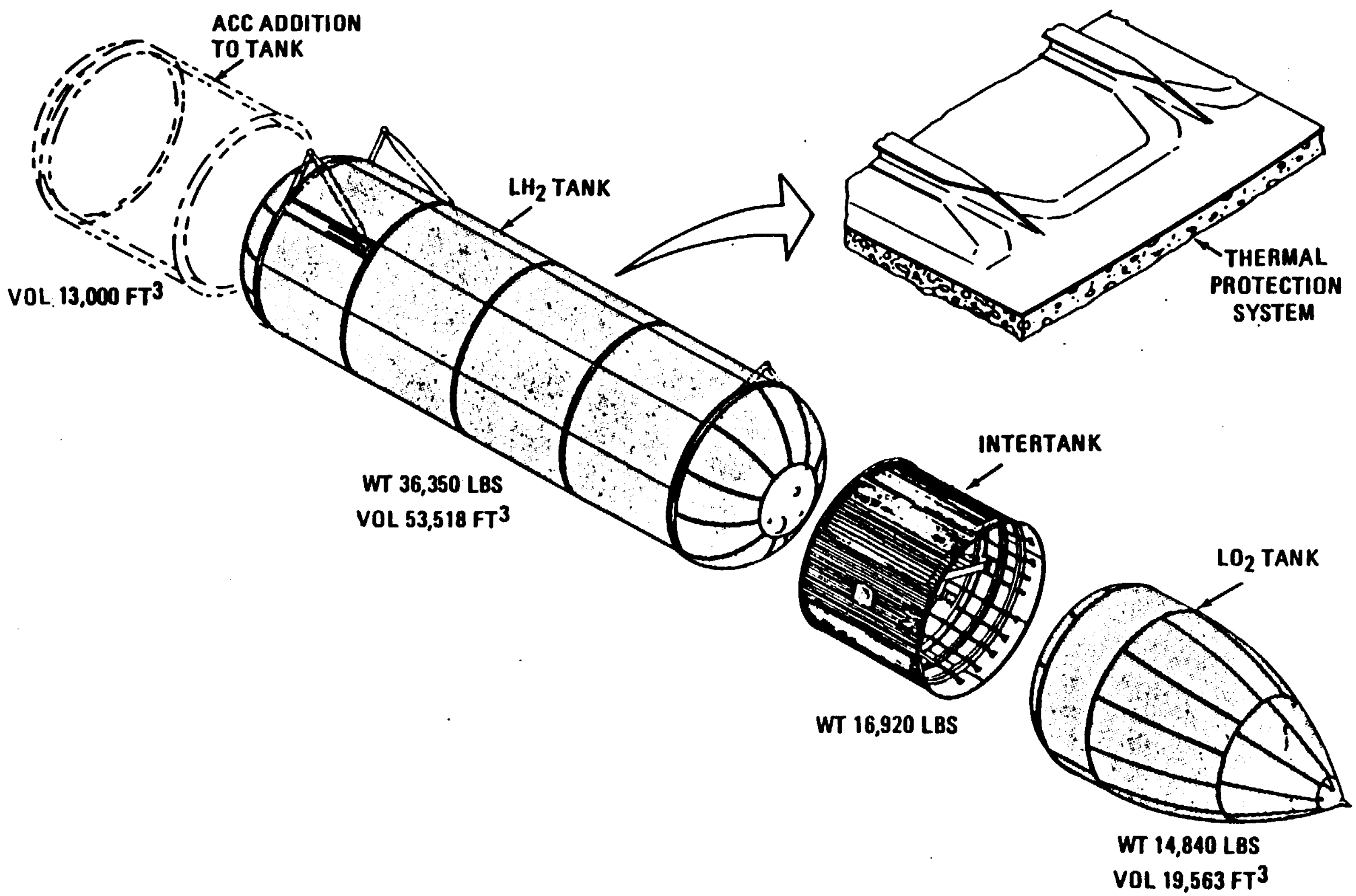


CONFIGURATION	PAYLOAD (LBS) 100 NM	160 NM	215 NM
ORBITER ONLY	72,300	65,000	52,000
ORBITER WITH ET	75,400	64,800	54,000
ORBITER WITH ET/ACC	70,000	59,400	48,600
ENHANCED STS WITH ET/ACC	86,000	75,000	65,000

NOTE: ORBITER/ET PERFORMANCE DATA DOES NOT INCLUDE DEORBIT SYSTEM, IF REQUIRED

FIGURE 2

The External Tank Is Adaptable For Alternative Uses



MARTIN MARIETTA

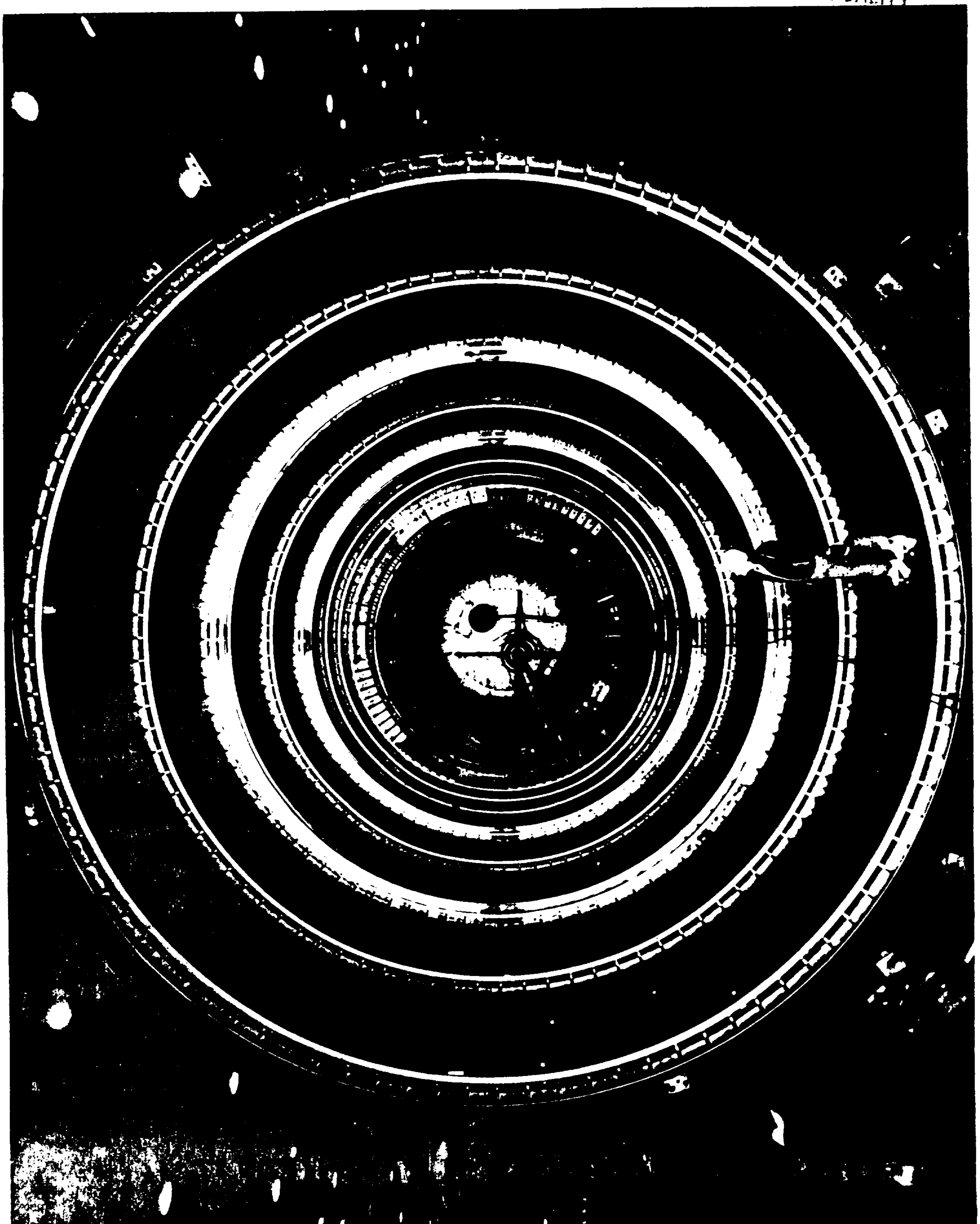
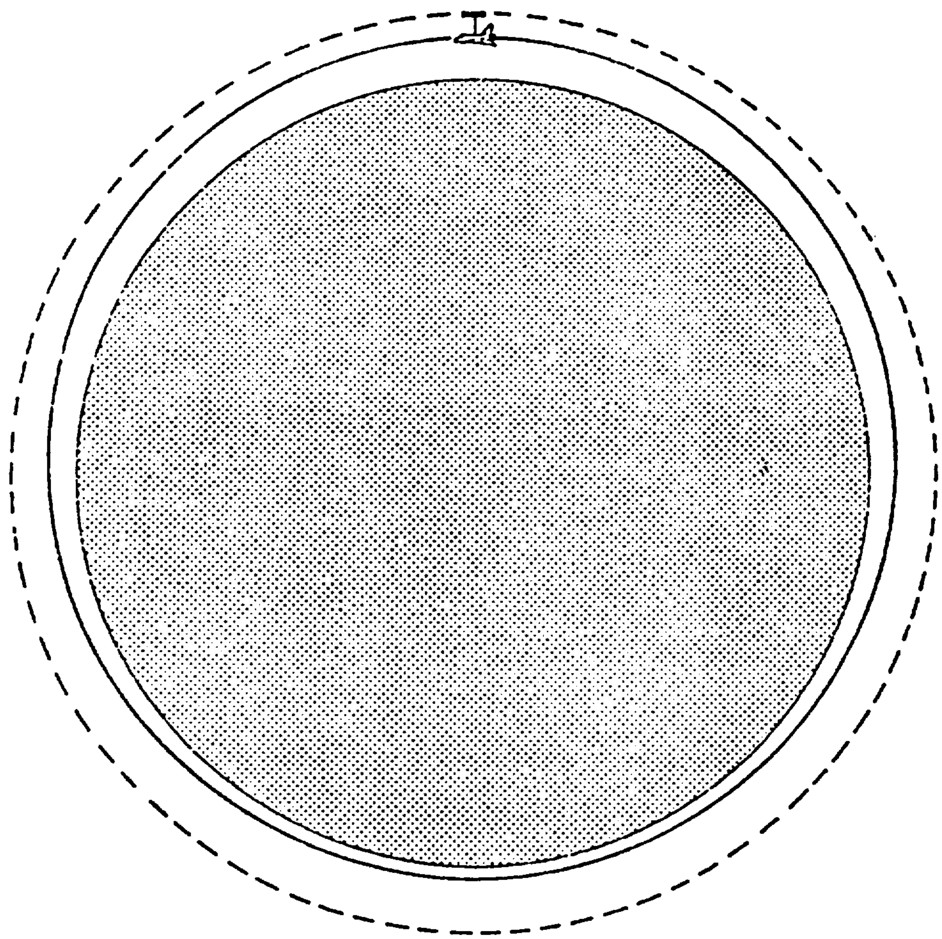


Figure 3.



While the Shuttle is at apogee of a 220-375 eccentric orbit, the release of the ET automatically injects the ET in a circular orbit at 400 km altitutde.

Smithsonian Astrophysical Observatory

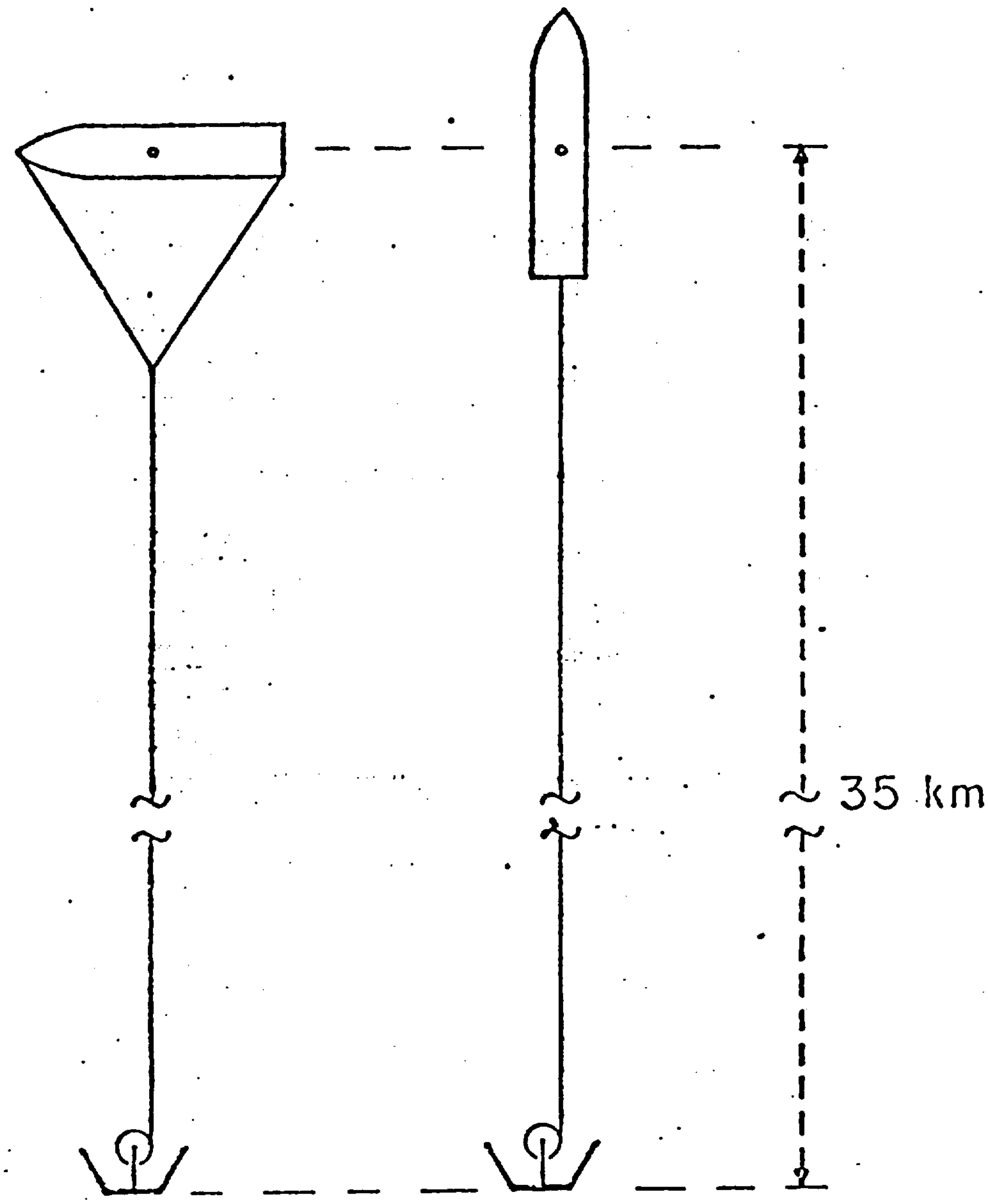


Figure 8. Two possible configurations of an External Tank plus PMDR (Pallet Mounted Deployer-Retriever). The left hand configuration is preferred because it has a lower A/M ratio than the right hand configuration.

External Tank

	WT. lbs.	% of Dry Wt.	
Forward tank	12,352	17.9	
Inter tank	12,080	17.5	
Aft tank, LH_2	28,900	41.9	
Separation Hardware	4,743	6.86	
Propulsion lines	3,760	5.45	Wt. metals
Miscellaneous	1,000	1.45	less misc.
			61,835
	62,835	91.06	
Insulation	6,190	8.94	
	69,025	100.00	

	% of total wt.	# of Material
Alloy 2219	64.44	44,480
2024	19.34	13,349
7050	3.3	2,278
7075	0.87	601
21-6-9	0.93	642
Inconel 718	0.44	304
Ti 6-4	0.31	214
	89.63	
Polyurethanes	5.54	3,824
Silicone Resin & Ablatives	2.37	1,636
Foams & Adhesives	1.03	711
Miscellaneous	1.45	1,001
	10.39	69,040

69,025

Al	=	56,490#	
Cu	=	3,450	
C	=	2,760	
O	=	1,725	
Si	=	690	
Fe	=	415	13 elements
Mg	=	268	from 200 to
Zn	=	173	35,000#
Ni	=	200	C, H , O , N
Ti	=	220	9 metallic or
Cr	=	188	metalloid
H	=	466	
N	=	246	
Others	=	1,807	(Co, Mo, V, etc)
		69,022	

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-OTHER DEPARTMENTS (3)

RAND CORPORATION (1)

TRW INC. (3)

LOCKHEED MISSILES & SP. (1)

HARVARD-SMITHSONIAN INST. ASTROPHYS. (1)

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II. SYSTEMS CONSIDERATIONS

A. Introduction
B. System Recommendations
C. Startup systems
D. Making the ET available for future use in space
E. Propellant recovery
F. ET use as a rigid strongback
G. Keeping the ET in orbit

A. Introduction

As discussed in much greater detail in other sections of this report, there are numerous uses for the External Tank as a structural element, as a source of structural materials, as a source of raw material, as a source of hydrogen and oxygen, and as a reservoir of angular momentum and kinetic energy. Each of these uses will have a number of system implications involving the Space Station, the Space Transportation System, and the ET by itself. It was not possible during this workshop to consider all these implications or to list them. However, some consideration was given to all suggested roles. In general, there appear to be no system implications which would preclude such roles.

As a part of the definition of the need for a space station, NASA Headquarters has issued a request to industry for a number of parallel studies pointed at defining of the mission requirements associated with a permanent presence in space. The contractors are being asked to research and define the viable uses for such a permanent presence and then to develop the associated mission requirements. Approximately 60% of the study effort is to be directed at this activity. After determining the mission requirements, approximately 30% of the study effort is to be directed toward defining attractive architectures for this permanent presence in space. The remaining 10% of the study effort will be directed at a preliminary analysis of the cost of this endeavor and the attendant programmatics and scheduling.

Eight companies or groups have been selected, and are at work:

Boeing	General Dynamics-Convair
Grumman/General Electric/Comsat	Lockheed Missiles and Space Co.
Martin-Marietta Aerospace	McDonnell-Douglas Aircrft Co. (Huntington Beach)
Rockwell International	TRW

A mid-term review of the efforts under these studies is scheduled for mid-November 1982. Final results will be available and a final review will be held in late February 1983.

It is hoped the preliminary study that we have done so far, investigating uses of the External Tank, will provide some helpful information to the aerospace investigators.

B. <u>System Recommendations</u>

The following are the specific recommendations of the systems group.

1. <u>Serious consideration should be given to the ET as part of the early space station architecture</u>. Besides the obvious benefit of providing a "safe haven" by reason of a large atmospheric volume, the ET would afford a maximum opportunity to explore and develop uses for it through actual practice.

Because of the regular delivery of the ET, design studies should also focus on utilizing many tanks in functional manners, not limited to the Space Station architecture. This should be done from the initial positioning of the first ET in orbit. Without aggressive advance planning economies of scale might be lost.

2. <u>It is recommended that the concept of a Cargo Volume (CV) added to the ET, be studied as a valuable utilization of the ET in orbit</u>. In this way an early use of the ET would be to carry out-sized payloads to orbit. In addition, propellant tanks fitted in this CV may be practical for propellant transfer in orbit or propellant recovery from the ET. Implementation of the CV will also provide operational experience for future utilization of the ET in orbit.

3. <u>Trade studies, including such influences as design and development, economics, operations and programmatics, should be conducted to determine whether the orbiter or the ET best serve the task of carrying propellants in orbit</u>. In the latter case, the ET already functions as a propellant carrier. The main problem is the transfer of the propellants to appropriate storage vessels once the STS is in orbit. If the orbiter were to serve as propellant carrier, inefficiencies might appear in container weight and design. The fundamental question is whether or not a propellant transfer system to recover propellants from the ET, a storage system and a loading facility for those propellants can really be cost effective in orbit? The impact of differing uses for the Space Station, the STS and the ET must be considered in any study of the merits of saving unused propellants from the ET.

4. Detailed consideration of the operations required to handle the ET in orbit must begin soon. This consideration includes enhancement of the ET to facilitate its use in space (see section D). Engineering consideration must also be given to the details of how the tank should be separated from the Orbiter in LEO, how it is stabilized and controlled during the critical phase when the tank is in close proximity to the Orbiter and how the tank is moved to its storage or use position. This operation could be done by manned EVA teleoperators, robots, a modification of the present Remote Manipulator Arm or a combination of all four. The safety and required effort need to be defined to remove doubts and to realistically determine the costs of retaining an ET in orbit.

5. <u>Who wants to use the tank and how much they want to pay for that use in time, materials and personnel must be considered in depth. The uses of the ET discussed in this report assume that a market for the</u>

tank exists. The possible markets of the tank, of course, hinge critically on its ability to be a worthwhile commodity. The markets should be looked at for the periods before, during and after the development of the space station. Study of the markets should not be limited to the aerospace industry. Non-aerospace customers might include petrochemical and biochemical processing sectors.

6. A low thrust level rocket engine should be considered for use on the ET. The engine should be coupled with a guidance and control package. It should operate on the propellants recovered from the tank. This unit could be used to move the STS into LEO without the Orbiter OMS. The system could also be used to move the ET into a higher orbit and maintain it in that orbit. The system might be given the capability to be removed for refurbishment either on the ground or at the space station.

7. A prerequisite to working routinely in space is a reliable, physiologically practical space suit. While most of these ET application concepts are feasible using RMS, teleoperators and robots, past experience would indicate that EVA will be required at some point for unforeseen contingencies. Past experience also indicates that routine manned access can add flexibility, reduce some costs and simplify systems.

8. The systems group wants to emphasize its agreement with several of the recommendations made in other sections of this report. These are as follows:

(a) Early testing of tether concepts (Sec. IV).

(b) Use of the ET as an occulter (Sec. VII)

(c) Concealment of payloads (Sec. III).

(d) Use of ET mass as shielding material (Sec. VIII).

C. Start-up Systems for Use with Present STS

Some key technologies are common to many of the potential applications of the ET. In many cases propulsion is involved either as a prerequisite to use of the tank or as a benefit deriving from the presence of the tank in orbit. Some of the possible early uses for the tank are discussed below.

An ET could be brought into orbit early to test the possible technologies to be used in its exploitation. As will be discussed in other sections of this report, near term experiments such as proof of tether concept, occultation platform, propellant transfer and storage unit testing, teleoperator and robotics hardware testing could be accomplished by using the tank as well as the Orbiter.

A concept utilizing tether technology could provide a near term small space station. Such a station would consist of an ET with basic structural hardware already fitted into place before launch, and a cargo compartment (possibly an ACC) with tether, winch, power and RCS. Temperature sensitive equipment and supplies could be carried in the Orbiter Payload Bay or the intertank volume of the ET and installed on the tank in orbit. The concept should not require continuous manning but should be programmed to expand to a continuously manned platform. If this concept is to be developed, more work must be done early.

Using the tank as a strong-back to support a more conventional space station concept is also possible. A General Dynamics/Convair idea utilizes an Orbiter-derived vehicle that begins with a single launch and then is expanded with follow-on STS missions (see Figure 1). The key use of the ET in this concept is based on its strength. Another feature of the ET that can be used is its volume. The tank can act as a reservoir with considerable inertia for the station's atmosphere. The tank could also be made into a shop either for pressurized or vacuum work.

D. Making the ET Available for Future Use in Space

Use of the ET in orbit is contingent upon keeping the cost of that use to a minimum. Therefore, every attempt must be made to keep modifications to the ET and the STS to a minimum. However, some modifications will be made. A set of minimum modifications that might be contemplated to enhance the use of the ET is listed below.

A minimum list includes the following:

1. A simple attitude control system would be needed for the orbiting ET. Such a system could provide an active ET for rendezvous and docking. The system could be stored on the ET in available space in the intertank region or in an ACC or other expanded storage area. If a more ambitious platform role for the ET is contemplated, a more sophisticated system for pointing and controlling the ET must be developed. By operating within the Navstar Global Positioning system some of the inherent complications with positioning could be reduced.

2. The access ports to the interiors of the LO_2 and LH_2 tanks must be made accessible. The ports are presently bolted with metal seals. Easily attachable air lock systems for access to the interior volumes are necessary.

3. The design of handling attachments for the exterior of the ET would aid in its exploitation as a resource in space. These attachments could be rails, or hardpoints to facilitate moving over the surface of a tank. Attachments would also be used for holding a number of tanks in place or for tether connections. (See also Chap. VII, section C.)

4. Some study should be made of methods of altering the geometry of the ET. These studies might include "nibblers," saws and shaped charges. This concept, too, is discussed in more detail elsewhere (Chap. IV).

5. It has been recently demonstrated at Johnson Space Center that the present STS space suit creates major difficulties because of its low

pressure (4.3 psi). This suit pressure entails an unacceptably high risk of "bends". A suit with a nominal pressure of eight psi is under development. A flight configuration demonstration unit is scheduled to be available by January 1983. Availability of an operational eight psi suit will permit immediate EVA without prebreathing or a bends hazard. This suit will significantly enhance the utility of man in the assembly and operation of on-orbit systems, including ET-based systems.

Other devices, such as the Manned Maneuvering Unit (MMU), tool kit, foot restraints, work stations, RMS adaptors, berthing aids, and a zero-torque wrench have already been designed and are awaiting production go-ahead. All these items, in conjunction with the new suit will serve to maximize the use of man in space in general and the exploitation of the recently discovered potential of the ET.

E. Propellant Recovery

During the Shuttle ascent, at main engine cut-off (MECO), a significant amount of liquid oxygen and hydrogen are left in the ET and engine feed lines.

The amount of residual propellant at MECO depends on several considerations. Abort reserves, flight performance reserves, safety reserves to prevent SSME damage, and ullage contribute to the total residual propellant. For our purposes an average residual mass of about 6800 kg (15000 lb) of propellants can be expected on each launch. Deliberate addition of marginal propellants for use in orbit is an important option.

The engineering problem is to extract that propellant in a liquid form before the heat generated during ascent vaporizes it. In addition, the tanks must be vented to maintain a pressure of two atmospheres to keep them from rupturing. Engineering studies have indicated that propellant recovery is feasible during the first 20 minutes after MECO by using a very small settling thrust. The propellants could be stored in an appropriate dewar in the Shuttle Cargo Bay or in the External Tank in either a modified intertank area or an Aft Cargo Compartment.

Preliminary study shows that the on-orbit storage time for LH_2 might extend well beyond the first hour after launch. If the LH_2 is kept at the rear (drain end) of the tank, the existing ablator/insulator that is to be applied to all Lightweight External Tanks after number four would keep heat transfer down to a point where the LH_2 could be kept liquid with only modest boiloff for as long as ten hours.

Using properly insulated vessels, LOX can be stored for many months (perhaps even years). Hydrogen may be storable for some months with only modest boil-off but this has to be looked at in more detail. Reliquefaction of LOX is probably feasible without great difficulty. Reliquefaction of hydrogen is complex.

Except at very high altitudes (probably 550 km), storage of low pressure gas in large bags results in prohibitive drag losses. High pressure storage requires considerable energy for compression and heavy tankage. Some of the energy may be extracted when the gas is relinquefied or otherwise released to a lower pressure (see below).

One method of storing hydrogen and oxygen in orbit is in the form of water. However, considerable energy is required to separate the components if they are to be used later as propellants.

If used quickly to reduce boil-off losses, the oxygen and hydrogen may not be reacted efficiently to recover much electricl energy using fuel cells or high-rate turbines. The water would have to be reconverted to LO_2 and LH_2 for use as propellant. Fueling an OTV from a water reservoir may call for capital and mass-intensive high peak power levels.

An obvious use for the residual propellant is in the refueling of Orbital Transfer Vehicles (OTV). Currently the Centaur F is planned to serve as the booster to move heavy payloads beyond LEO. The Centaur, which will become operational in the last half of this decade, will have a propellant capacity of 19,720 kg. Currently the Centaur F will be boosted into LEO fully loaded in the Orbiter paylaod bay. Alternatively, the propellants for the Centaur could be loaded from the ET after MECO. That is the fuel for the Centaur could be carried into orbit in the ET and transferred after launch.

A more advanced OTV concept, proposed by O'Neill (1978) is to use the shredded metal from the ET as fuel for a mass-driver reaction engine. At a nominal 12 launches per year, approximately 400 tons of reaction mass could become available from the ET. Using O'Neill's baseline configuration, it would be possible to launch about 250 tons per year of payload to GEO.

Another use of propellants recovered is for power from conventional fuel cells. LH_2 and LO_2 in large amounts would be required to run a fuel cell powered space station. Recovery of the propellants from the ET would ease payload bay safety and space problems. For the space station, the redundancy inherent in using ten or more fuel cells of the same class as in use now on the Orbiter, as recommended by the Fletcher committee, is appealing.

Other minor uses include oxygen for crew life support. When converted to water, uses for life support or thermal control appear reasonable. The hydrogen could be used as propellant directly if it could be heated sufficiently. In addition, high electrical power levels for relatively short periods could be obtained by burning the propellants in a turbine.

F. Use as a Rigid Strongback

The fact that the ET is a rigid structure capable of supporting itself under one gravity raises some other interesting possibilities for its use in space as well.

The tank holds promise for use as a strongback for various applications. For instance, as mentioned earlier in this section, the tank can form the basis of a free flying space station of the type suggested by General Dynamics-Convair. Designs by other aerospace groups also use the strength of the tank as well as its volume.

The tank could be used as a mount for large antennae, of the size range seven meters or more in diameter. If designed around a tank as support structure, an array of several large antennae might be useful in LEO for communications purposes.

As will be developed in the science and application section, antenna arrays can be used in Earth sensing and astronomy. The tank could act as a strongback to hold millimeter telescopes (see Sec. V) in either down looking or up looking modes. Two or three tanks bound rigidly end-to-end could be the optical bench for interferometry in the UV/visible or IR wavelengths.

G. Keeping the ET in Orbit

One of the primary considerations in using the ET in LEO is keeping it there. Available technology capable of doing this now exists. There are also other means of accomplishing the task. Two methods of keeping the tank in orbit are discussed in the section on tethers (Sec. III). These are first, holding the ET in a low-drag attitude with a kilometer long tether and a one-ton mass and second, using tether dynamics to loft the ET into a higher orbit while aiding the Orbiter in its deorbit manuever.

A cryogenic propellant rocket engine, such as the RL10 used on the Centaur or a smaller engine, could be used with a guidance and control package to maintain the ET in LEO after separation from the Orbiter. Cryogenic engine technology is well developed and could be applied fairly quickly.

An engine developed or modified for use on the ET could be a forerunner power plant for an OTV.

Another method is the hot H_2 rocket. This rocket engine uses H_2 gas. A system is currently being developed with Air Force support at the Rocket Propulsion Laboratory (RPL) which utilizes solar heated hydrogen for the propulsive power. The present expectation is that a specific impulse of about 800 sec. can be attained, with some models rated at over 1000 sec. Such models use particulate heat exchangers to raise the operating temperature.

The test apparatus at RPL uses a 20-ft diameter solar collector that should provide one pound of thrust in the experimental model. The weight of the system is in the solar collector. The actual engine for a two pound thrust version would weigh about five pounds.

The gaseous H_2 and O_2 in the tanks might be considered for use as rocket propellants. The fact that two tons of gaseous H_2 and O_2 are in the ET after MECO, opens the possibility of using gases in a small low pressure gas fed rocket engine. The mass of the gas available after the

ET is in LEO could boost the ET into an orbit 215 NM higher than its initial circular orbit over a span of a few days. Additionally the very low-g acceleration provided by such engines might ease crew transition to weightlessness. Such low thrust engines might also have a role in preparing a spacecraft for a mission to Mars.

Storable propellant technology is also available. A modified OMS/RCS pad based on what is now in use on the Orbiter could be used to maneuver the ET in orbit.

Electric propulsion is another possibility. The technologies have been studied extensively since the 1960's. The referenced review by Fearn (ref. 10) gives details.

Electric propulsion might also have a place in moving some payloads to GEO. Daily and Lovberg (ref. 11) have looked at the best specific impulse for LEO and GEO missions. The optimum range, they believe, is 1500 to 3000 seconds. There are several possible engine types that could provide propulsion in this range.

The brief discussion presented here is for illustration only. It shows the basis for our confidence that an ET, or ET-based space station, can be kept in orbit indefinitely, or boosted as required.

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CONFIGURATION PERMITS ACCESS TO EXTERNAL TANK THROUGH COMMAND MODULE

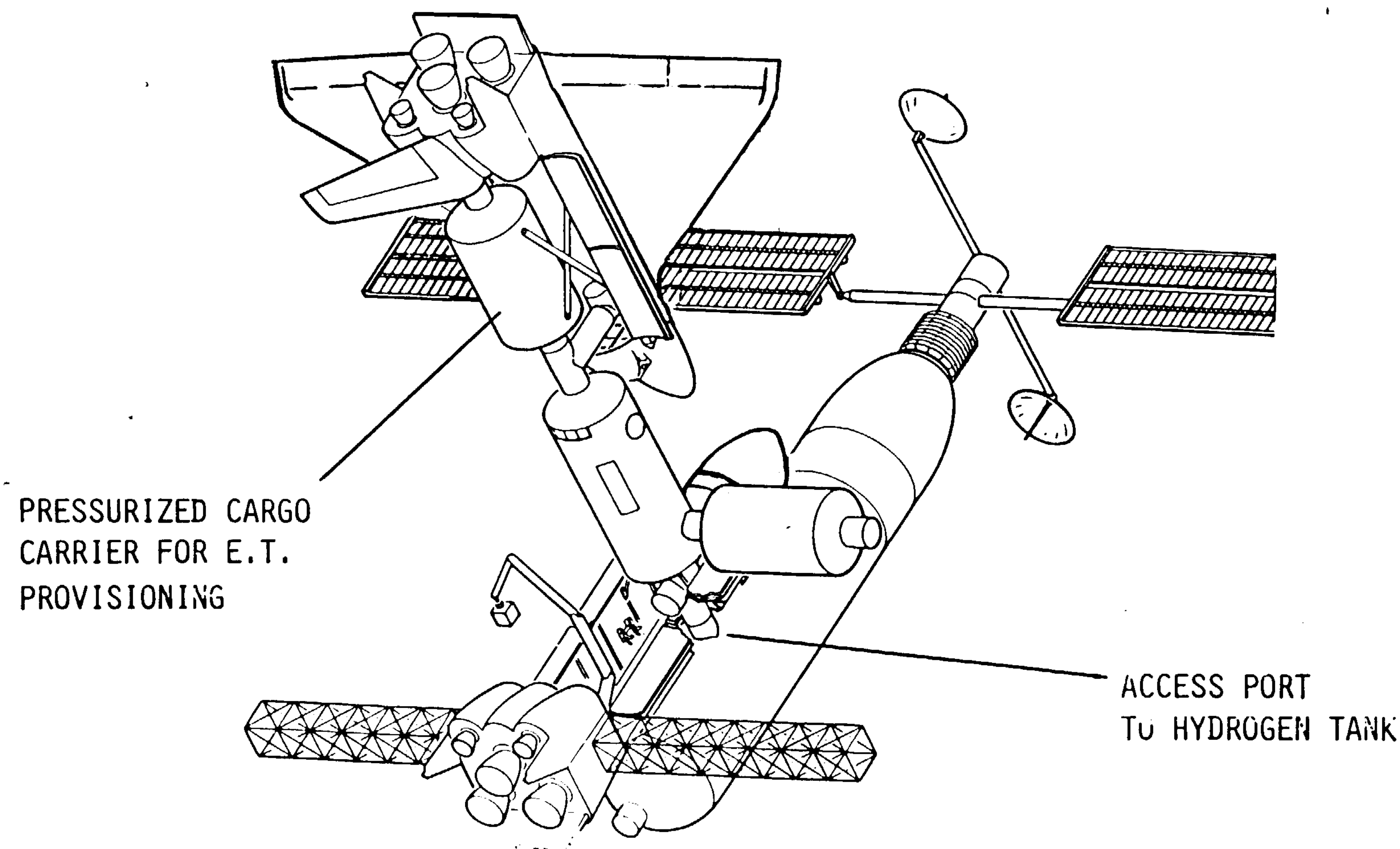

Figure 1.

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III. TETHERS AND EXTERNAL TANKS

A. RECOMMENDED ACTIONS:

1. The Tethered Sub-satellite should be flown at the earliest possible date, as a proof-of-concept experiment for tether techniques.

   This is a highest priority mission because the large potential benefits of tether techniques in a wide range of applications cannot be incorporated in planning, much less realized, until such a proof-of-concept experiment is flown. The TSS hardware is suitable for the most important tests of a wide range of tether operations, so an early flight of the TSS will allow the prompt exploitation of many promising tether techniques.

2. A full-scale experiment involving storage of one or more tethered ETs in orbit should also begin the planning stages promptly.

   Use of equipment developed for and proven by TSS experiments could reduce development time and expense for such an experiment.

3. Analytical, simulation, and experimental work on tether-related issues should be expanded beyond the scope of the current TSS project.

   In particular, more work should be done in the following areas:

   a. Tether materials & hardware for long-term use in space
   b. Control laws for generating large but precisely controlled librations
   c. Procedures and hardware requirements for tether-mediated rendezvous
   d. Electrodynamics of tethers, particularly for power generation
   e. Tether applications that enhance space station capabilities
   f. Space station tradeoffs: single mass vs plural tethered masses

4. Tether techniques for stabilization, artificial gravity, and momentum changes (particularly with external tanks) should be formally included on all relevant existing lists of potential STS performance enhancements.

   Some enhancements will be required for the STS to reach planned levels of performance, and in many cases tether techniques may well be more practical and cost-effective than other types of enhancements.

B. INTRODUCTION: TETHERS AND EXTERNAL TANKS

The major way that tethers can enhance the Space Transportation System is to provide momentum transfer with reduced use of expendables such as rocket propellants. Besides momentum transfer, tethers can also provide an easily adjustable gravity field with a minimum of Coriolis effects, and—particularly as part of active systems—can stabilize spacecraft or ETs despite disturbing torques. Electrically conducting tethers may also be able to serve as part of a propulsion system (Drell et al., 1965) or as antennas (Grossi, 1973).

Use of tethered satellites with the STS for scientific purposes was first proposed in 1974 by Dr. Guiseppe Colombo (Smithsonian Astrophysical Observatory and the University of Padua). Most of the work since then on this and other tether concepts has been done by him or by groups under his direction in the U.S. and in Italy.

In concert with tethers, orbiting external tanks have two key roles. The first is momentum storage. In conventional space operations, extra mass is more a liability than an asset. However with tethers, added mass acts as a bank for storing momentum and energy. Putting ETs into orbit could double the mass "throughput" of the STS, and this added mass could be a significant asset for many tether applications.

The second tank role is structural. Transferring momentum to and from payloads and orbiters places structural loads on the momentum bank, whether that bank is a space station or simply a tank farm. The ET is the structural backbone of the STS at launch, and it might serve a comparable function for orbiting momentum banks.

It must be stressed that the intent here is not to wed tether and ET applications irreversibly, so that they stand or fall together. The TSS concept clearly shows roles for tethers without ETs, and most of this report lists roles for ETs without tethers. The special role of this section and Appendix II is to highlight synergistic applications of tethers and ETs.

C. TUTORIAL ON GRAVITY GRADIENTS, TETHERS, AND MOMENTUM EXCHANGE

For those unfamiliar with gravity gradient and tether concepts, we begin with a simple example and let it evolve gradually into the systems of most interest. Then a few useful equations are presented in simplified form. Readers interested in more detailed treatments can consult Appendix II or the references.

Gravity-Gradient Stabilization

The gravitational potential energy and (for circular orbit) the total energy of a small body near a large one vary inversely with the distance R from the center of mass. The graph of (-G/R) is convex upward, and is steeper at smaller R. Thus if we have a double mass (say a dumbbell) in orbit, with its center of mass at fixed R, its energy will be lower when it is vertical than when it is horizontal: on an energy graph, the dumbbell will tend to sit astride the local convexity rather than on top of it:

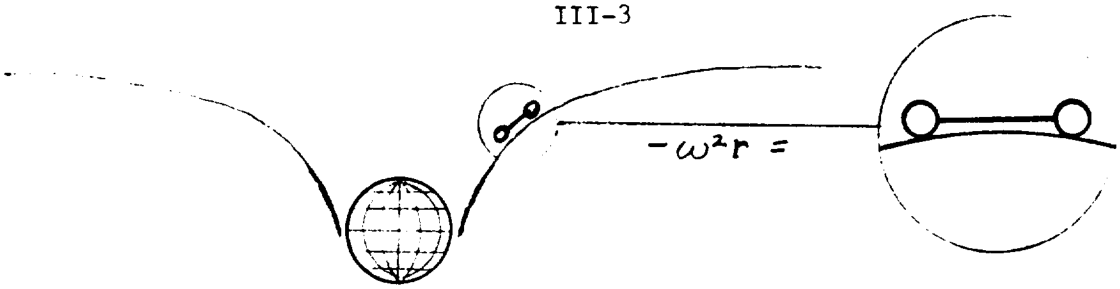

Figure 1. Simple model of "gravity-well" and gravity gradient effect

The same holds of other elongated objects such as External Tanks. The effect is small when the object is small, but other forces that can affect orientation, such as off-center aerodynamic drag and light pressure, are also very small. Thus the External Tank tends to end up vertical. As found in Appendix II, this makes the tank's orbit decay 4 times faster than it would in an end-on position. This small effect thus can have large impacts. Two other small effects with large impacts—artificial gravity and momentum exchange—are discussed next.

Artificial Gravity

Observers at each end of a dumbbell will experience an apparent gravity, towards the earth for the inner end and away from it for the outer one. This is because the inner mass is moving too slow for a normal orbit and the outer mass is moving too fast. The effect grows linearly with the vertical distance from the freely-orbiting "zero-gee" point near the center of the dumbbell, and is inversely proportional to the cube of the orbital radius. In LEO it is .4 milligee per kilometer from the zero-gee point.

This "gravity gradient" effect (a third of which is actually a gradient in centrifugal force) can provide a sense of weight with far lower levels of physiologically disturbing rotational effects than provided by small spinning space stations. In addition, the fixed apparent direction of earth from the ends makes earth observation far more practical.

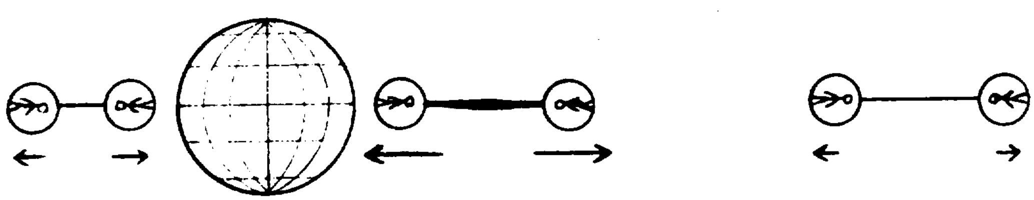

Figure 2. Artificial gravity in dumbbell satellites

Doubling the length of a dumbbell also doubles the tension on the beam, so the required beam mass is quadrupled. For beams several hundred kilometers long, the beam mass becomes comparable to the end masses, and a tapered beam becomes necessary. For much shorter beams, beam mass can be trivial.

Gravity Gradient Pendulum Behavior

If a dumbbell is placed at an oblique angle with respect to the vertical, the gravity gradient forces create a torque that tends to move it back toward the vertical. Thus such a dumbbell becomes a pendulum that oscillates, or librates, about the line between it and the center of the earth:

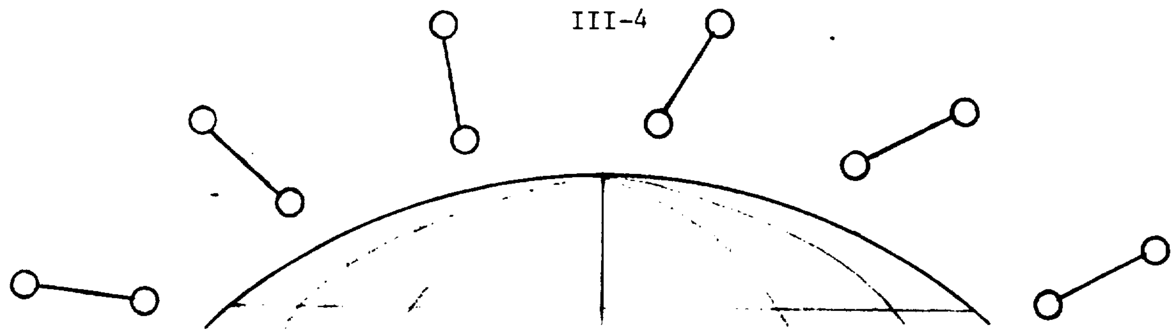

Figure 3. In-plane gravity gradient pendulum behavior

Libration periods for such a gravity-gradient pendulum are independent of tether length, because for any given angular amplitude, the displacements and restoring forces both grow linearly with pendulum length. This means that if the dumbbell beam is replaced by a flexible tether, the tether should swing solidly, rather than with the tether leading the tip masses as with the chain of a child's swing. Characteristic periods are very long: nearly an hour.

For small librations, periods are also independent of amplitude. For large librations, the periods increase approximately with the square root of the secant, because restoring torques scale with (sin * cos). Smearing the mass out so it is less one-dimensional (e.g., the ET itself) also increases the periods, just as moving some mass above the hinge of an ordinary pendulum does: the moment of inertia about the orbital axis may not change, but the restoring torques decrease.

For small in-plane librations, the characteristic period is Sqrt(1/3) of the orbital period, or .577 orbit. Small transverse librations see the same gravity-gradients, but the characteristic period is Sqrt(1/4) of an orbit, or .5 orbit. This is due to another restoring force: even without a connecting beam, transversely displaced masses still "librate" once per orbit, since they are in distinct orbital planes.

During librations, tensile loads in a dumbbell beam are less at the ends of a swing than in the middle. Due to Coriolis effects they are less during counter-swings than during swings in the same sense as orbital rotation. For in-plane librations with more than a 66 degree half-angle, beam loads actually become slightly compressive near the extremes of each counter-swing. Thus two masses connected by a flexible tether can only behave the same as a dumbbell if they do not experience large counter-swings; then they can become part-time free-flyers. (This can be prevented by reeling in slack at those times.)

Because gravity gradients are in both directions away from the zero-gee trajectory, a dumbbell that swings past 90 degrees begins accelerating again, and becomes an unevenly spinning rotor instead of a pendulum. But if energy can be pulled out of the spin after the dumbbell flips over, it can be trapped into "upside down" (but equally stable) pendulum behavior.

Momentum Exchange with Variable Length Systems

Now let us imagine replacing our dumbbell beam with a tether and winch, so that we can alter the length of the system. Paying out tether gradually decreases the orbital radius of the inner mass and increases that of the outer mass. Now the tangential velocity of the lower dumbbell mass is too high for the mean orbital rotation rate, and the tangential velocity of the upper mass, too low. Thus the lower mass swings forward and the upper mass backwards. The tangential component of tether tension then slows down the lower mass and speeds up the upper mass.

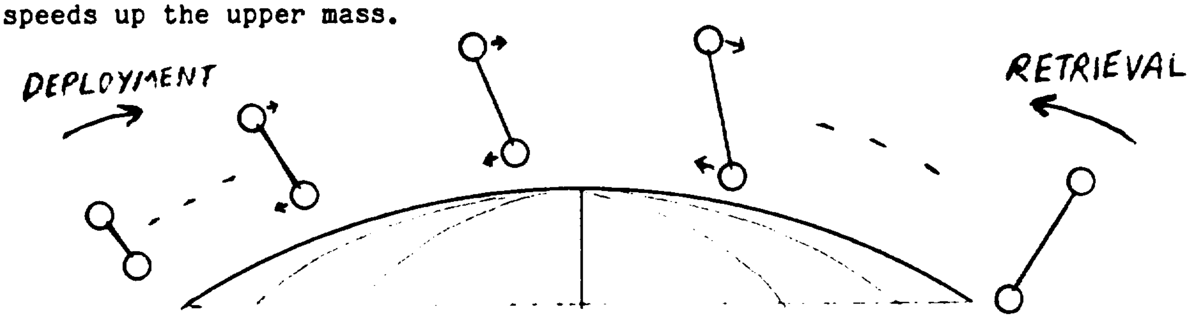

Figure 4. Momentum exchange during tether deployment and retrieval

This occurs only during deployment; after that stops and any librations die out, the tether is again vertical. However the upper mass has in effect now "stolen" momentum and energy from the lower mass, and is both higher and faster-moving than before. In addition, some energy has been dissipated in the reel brake, since tether was let out under tension. (Reeling in tether reverses the temporary deployment tilt and thus speeds up the lower mass and slows down the upper one. Reeling in the tether also requires energy.)

Release of Tethered Masses into Free Orbits

If we now cut the tether joining two masses, the masses follow new free-orbit trajectories. At the point of release, they are 1 tether-length apart. If the tether is hanging vertically when the masses are released, then halfway around the earth from the release point, they will be 7 times as far apart. However, if the tether is swinging like a pendulum at the time of release, the second trajectory separation can be varied from .7 to 13.9 times the original tether length, depending on the pendulum direction and libration amplitude. Thus tethers can be used to cause large but controlled orbit changes. They can complement or even entirely replace rockets in some applications, and may at times even eliminate any need for guidance systems on released objects.

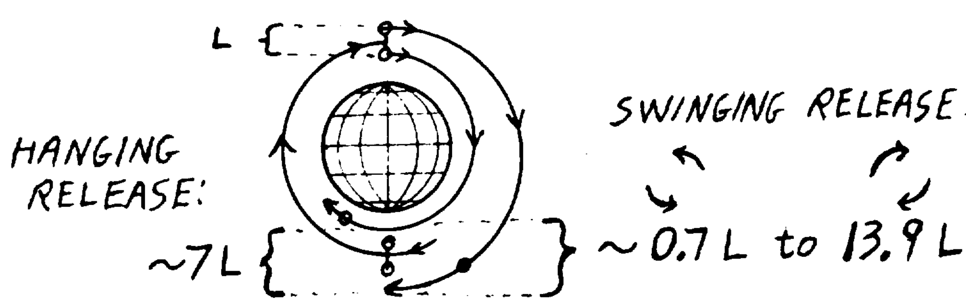

Figure 5. Trajectories after release from hanging and swinging tethers

Equations for a Gravity-Gradient Pendulum

The treatment so far has been qualitative. The equations that describe the most important aspects of gravity-gradient pendulum behavior follow, in simplified form. (Second-order effects cause variations in center-of-mass orbital radius and displace the zero-gee point on the tether from the center of mass. These effects are neglected here because they are quite small: under 20 meters in the case of the proposed 100 km Tethered Sub-Satellite.)

If two masses x and y are initially together in near-circular orbit with radius Rxy, and are then deployed apart with a lightweight tether of length Lt, the effective tether length from the zero-gee point to mass x is:

$$|Lx| = Lt\ y/(x+y) \qquad \{Lx<0 \text{ if } x = \text{lower mass}\}$$

On a swinging pendulum, apparent gravitational acceleration, Ag, depends on Lx and the current and maximum libration half-angles, Ax and Ah. The square root term in the following approximation is added when the pendulum swing is in the same sense as orbital rotation and subtracted when counter to it:

$$Agx = 3\ G\ Lx\ R_{xy}^{-3}\ [\mathrm{Cos}^2(Ax) + F \pm \sqrt{1.333\ F}\ ]$$

$$\text{where } F = \mathrm{Sin}^2(Ah) - \mathrm{Sin}^2(Ax)$$

As a pendulum passes through the vertical, the relative velocity between point x and a co-planar freely orbiting object at the same altitude is:

$$Vx-Vo = Lx\sqrt{G/Rxy^3}\ (1.5 + 1.732\ \mathrm{Sin}(Ah)) \qquad \{\text{Counter-rotation: } Ah<0\}$$

An object deployed and released from a tether as it hangs vertically or swings through the vertical will go into an new orbit. Distances between the the original orbital path (before tether deployment) and the final path are:

$$R0-Rxy = Lx \qquad \{\text{at point of release}\}$$
$$R180-Rxy >= Lx\ (7 + 6.928\ \mathrm{Sin}(Ah)) \qquad \{180 \text{ degrees later}\}$$

The ">=" indicates that higher-order effects make the absolute value of (R180-Rxy) slightly larger if x above the zero-gee point (Lx>0), and smaller if it is below. The second equation does not apply to counter-rotating swings with amplitudes beyond 66 degrees (Ah<-66), since the tether goes slack near the extremes of those swings. Since (R180-Rxy) can be nearly 14 Lx, a tether as short as 25 km can be used to cause reentry of objects originally in orbits as high as 400 km.

The two equations above estimate separations between orbital trajectories of low eccentricity. If release is made from a pendulum in a very elliptical orbit, or at a point other than the vertical during a swing, or from tethers many hundreds of kilometers long, precise orbital paths must be calculated from conditions at release.

Release at points on a swing other than the vertical has less dramatic impact on orbital parameters, because then Vx-Vo has less than half an orbit to take effect as an altitude change. However, off-vertical release may have advantages in some cases. Similarly, release during transverse librations may also be useful at times.

Tether Controls

The above descriptions of tether behavior make such statements as "after librations die out...", without investigating how they are damped or whether there might be forces that continually drive libration. (There are in fact such forces, the most important of which is a transverse component of drag.)

The discussion of controls below is very brief, since much of the technical literature and several of the patents on tethers are precisely concerned with this subject.

In low earth orbits that are not perfectly equatorial, rotation of the earth causes an out-of-plane component of the aerodynamic drag force. This is in opposite directions each time the satellite passes the equator. If the satellite experiences different air densities on the two passes (due to an elliptical orbit or different solar heating effects), the result is a force variation that can excite transverse librations. Adjusting the ellipticity of the orbit for equal drag on day and night sides, or raising altitude to cut drag on both sides, can minimize the problem.

Remaining control problems can be dealt with by varying tether length according to the following general rule: deploy tether when tension is more than usual, and take it back when tension is less than usual. This "yoyo" station-keeping process clearly pulls energy out of the system. It can damp moderate in-plane and transverse librations simultaneously since they have different periods. The same goes for any shorter-period higher-order tether vibrations.

In the case of tethers without much mass at one end (such as in some of the more ambitious tether applications to be described later), higher-order tether oscillations slow down, and damping all possible excited modes at the same time may become difficult. Further work is required to determine whether this might be a problem.

Tether Retrieval Problems

If one deploys a tether two separate times, the effects of differences in initial states become less important as tether is paid out, because longer systems require more energy for equal libration amplitude. However, during retrieval, small librations are magnified, so retrieval control laws require feedback for stability. Retrieval rates seem to be limited far more by the low rate at which transverse librations can be damped than by limits on the rate at which spin angular momentum can be bled out of the shortening system's once-per-orbit spin rate. (This angular momentum goes back into the orbital angular momentum, from which it originally came.)

Intentional Librations

To this point, it has been assumed that tether librations are always bad and should always be damped out. However, controlled libration can provide useful capabilities, such as release of (or soft rendezvous with) objects in a variety of trajectories, and even (in a reversible version of the earth-moon tidal history) minor adjustments in orbital period and thus phase, to either permit or prevent rendezvous with another object.

Tether controls described earlier can be reversed to increase librations, by reeling tether in when tension is high and out when tension is low in much the same way that a child "pumps" a swing. This can even set an initially vertical system rapidly spinning. Amplifying transverse librations is also possible, but takes much longer.

D. TETHER-MEDIATED RENDEZVOUS

We have already discussed using tethers to release objects into separate trajectories. Trajectories for velocity-matching tether-mediated rendezvous are simply a mirror-image in time of release trajectories. Thus tethers can allow rendezvous between objects with quite different energy levels.

In addition, tethers may allow safe capture of objects with unpredictable responses, such as malfunctioning satellites. First contact can be made at the tip of the tether, kilometers away from the orbiter or other tether facility. The maneuvering/grappling unit at the tether end might be sturdy, relatively inexpensive, and—most importantly—unmanned. A useful aspect for development is that tether-tip maneuvering units may be easier to test realistically on the ground than free-flyers are.

Tether-mediated rendezvous techniques would probably first be used for capturing unmanned objects, but after adequate testing might also be used with manned vehicles.

There are several practical constraints on tether-mediated rendezvous. The most important are that timing is more critical than usual and loads after docking with long tethers can be significant, both on tether and on tip mass.

Rendezvous with a "flying trapeze" may seem impractical, but there are two major advantages here compared to familiar applications such as mid-air refueling. The first is that the system is far more predictable: there are no large random inputs such as air turbulence. As a result position and velocity matching should be easier. The other advantage is that relative accelerations for most applications can be kept below 1% of a *gee*. Deploying additional tether might extend the docking window somewhat, and low levels of thrust by the object to be captured can extend it as much as desired.

For equal orbital energy differences, accelerations at rendezvous are least if vertical or slightly counter-swinging tethers are used, so tether-mediated rendezvous may be most practical under those conditions.

Immediately after docking, a tether starts to stretch in response to the new load, and maximum loads may be twice the steady-state loads. Rendezvous control laws might be able to reduce these transient loads by anticipating tether stretch and reeling in enough tether to compensate. Such controllers would be most valuable on very long tethers (100 km or longer). Tensile waves can take 10 seconds to travel 100 km, so design of an anticipatory controller for such applications may be practical.

Regression of Nodal Lines

A rendezvous constraint that is particularly relevant to "swarm of bees" space station concepts is differential regression of nodal lines. The earth's equatorial bulge causes an object in any orbit crossing the equator obliquely to cross the equator further westward each orbit. The right ascension can regress as much as 9 degrees per day for low near-equatorial orbits, but the regression rate decreases with inclination and orbital radius R as follows (based on a fit to Fig. 3.1-5 of Bate, Mueller, & White):

$$\text{Regression} = 10\ \text{degrees/day}\ \ \text{Cos(Inclination)}\ \ (6378\ \text{km}/R)^{3.5}$$

Two objects in 28.5 degree inclination orbits and at altitudes of 400 and 490 km become coplanar again every 3 years; at 400 and 700 km, every year. Differential regression rates that large may actually be advantageous, if reliable rendezvous techniques can be developed.

For example, ETs and long-life free-flyers might be inserted into any 28.5 degree orbit high enough for long storage. Later they would be retrieved by a lower-altitude orbiting tether facility (which is either a space station itself or part of a space-station swarm), when the tank and tether facility again become coplanar. A second tether facility with the same inclination would double plane-matching frequencies, and might eventually be justified. Satellites requiring frequent or irregular service might have to be kept at space station altitude.

E. TRADEOFFS IN USING TETHERS FOR MOMENTUM TRANSFER

Tether systems and chemical or ion rocket propulsion systems both have working masses (tether, propellants), and both have "overhead" mass (reels, motors, solar cells, rocket engines, tankage, etc.). Tether systems have some of the advantages of chemical rockets (high momentum transfer rates, moderate electric power), and some of the advantages of ion rockets (the mass is an investment rather than an expense, and can be reused).

For very large delta-Vs, tethers alone are impractical, but tether/rocket combinations are better than rockets alone. The rule that maximizes the mass savings over a rockets-only operation is to make the marginal tether specific impulse (which is half the average impulse) equal that of the rocket, with the relevant marginal overhead masses included in both comparisons.

The optimum for single-use tethers (which need not be rewound and hence might have fairly low overhead mass) seems to be a tether with Vx-Vo near 100 m/s. Such a tether might weigh about 1% as much as the payload, and should displace about twice its weight in H_2/O_2 propellants.

The working and overhead masses of a tether system are reusable. Best tether lengths for tether/rocket combinations at first grow linearly with the number of uses. For example, with a design life of only 15 operations (either rendezvous or release), and including overhead mass penalties of twice the working mass, the optimum mix of tethers and rocket for large delta-Vs should be to provide about .5 km/sec with tethers and the rest with chemical rockets.

Eventually, at delta-Vs near .7 km/sec, tethers made of Kevlar or similar strength/weight ratio materials begin to suffer from serious self-loading problems, and the required tether mass then grows with the exponential of the square of the delta-V. The optimum tether length and delta-V grow much more slowly after that point. For Kevlar the optimum tether Vx-Vo seems unlikely to go much beyond 1-1.2 km/sec unless the tether receives heavy use or has other beneficial systems impacts, such as safety or elimination of many small guidance systems.

Delta-Vs twice as large can be provided by a tether facility in eccentric orbit, with perigee velocity halfway between circular and the desired high-energy condition. At its perigee it would capture a payload below it, and at a later perigee it would release the payload upwards. An issue with such a facility is differential regression between it and a space station. Payload transfer windows may be severely limiting unless the facility is primarily operated independently of the station.

The rough comparison above of tethers and rockets assumes that reaction masses much larger than the payload are available. However the results often do not change much when comparable masses are used, for the following reason. When two spacecraft separate, delta-Vs are generally advantageous for both: orbiter up and ET down (or vice versa); payload up and orbiter down; space station up and orbiter down, space station up and debris down, etc. If both masses are comparable, then twice as much tether is required for the same delta-V at each end (since Lt = Lx+Ly), but both delta-Vs have value.

A final difference between tethers and rockets is that, in the long run, a massive tether facility cannot provide a net momentum in one direction: it merely serves as a repository of temporary momentum imbalances in the overall flow of traffic. If net momentum is needed in one direction (or if drag has the same effect), then chemical rockets, ion rockets, mass drivers using ET materials, Alfven engines, or other thrusters must cancel the imbalance.

But it is only the momentum imbalance that must be provided by thrusters. With the STS, most of the mass reaching MECO eventually returns to earth, so a massive tether facility might need only a very small thruster, used only when power is available, to pay for much of the net mass transport away from earth.

Tradeoffs Between Vertical and Swinging Tether Operations

A brief comparison should be made between long tethers designed only for gravity gradient loads, and shorter thicker tethers designed also for pendulum loads. For use at amplitudes of 60-90 degrees, a given length of pendulum tether must be 2.75-3.15 times as strong as a comparable length of vertical tether. But this is an unfair comparison, because for equal total (potential plus kinetic) energy transfer, such a pendulum tether can be shortened and lightened 43-46%; as a result it ends up 10% less massive.

If the purpose is equal perigee change for reentry, a pendulum tether can be 20% less massive. If the mission is a boost to GEO or beyond, then pendulum tethers can be 15-25% lighter than hanging tethers. Systems with long tapered tethers can have much larger mass-savings, due to exponential effects.

For rendezvous, the critical issue is likely to be not tether loads but relative accelerations. As discussed above, these are minimized by a hanging or slightly counter-swinging tether. A system designed for swinging release loads will have more than adequate strength for vertical rendezvous loads, but since higher safety margins are needed for rendezvous transients, the extra strength is useful.

Likewise, even if a tether is sized only for hanging loads with a "design load" such as the orbiter, it can be used in the pendulum mode with smaller payloads. For much smaller payloads it is even possible to "pump" the system up to a fairly significant spin, for a higher release velocity than can be provided by a pendulum swing. This process can only be carried so far, since very high velocities demand a tapered profile near the tip that is optimized for a given payload/tip speed combination.

A further consideration is that the pendulum mode allows rendezvous and release with a wider range of orbit pairs: from concentric (for large counter-swings), to orbits having 13.9:1 variations in separation distance (for large swings in the sense of orbital rotation), and even to slight plane mis-matches (for large transverse librations). Such operational flexibility may in the long run be the major advantage of pendulum-mode operations.

F. TETHER MATERIALS

For short tethers, a variety of tether materials can be used with little mass penalty. However, more ambitious applications require careful choice of tether materials and construction for the intended use. Tethers for these applications must have very high usable specific tensile strength and must be able to withstand exposure to the space environment.

The aramid polymer fiber Kevlar, developed around 1970 by DuPont, is currently the favored material because of its extremely high tensile strength (2.8E9 pascals or 410,000 psi) and low density of 1.44. The fraction of the test strength realizable in a tether is about 60%, and for long life the maximum loads have to be kept under 70% of the short-term breaking strength. Thus the specific strength (expressed as the maximum length of a tether that can support itself in full earth gravity for some time) is about 84 km. With an additional safety factor of 1.7, the specific strength usable for design purposes is about 50 km in full earth gravity.

Specific strength (strength/density) has the same dimensions as velocity squared. Such a "characteristic velocity", Vc, has physical meaning: for a spinning ring made of the tether material, Vc is the velocity at which self-induced centrifugal hoop stresses equal the material strength. More to the point here, in untapered gravity-gradient tethers of lengths such that Vx-Vo = Vc, the maximum self-induced stress at the tether mid-point is 67% of tether strength for hanging tethers, and 45% for widely librating tethers. If Kevlar has usable specific strengths near 50 km, then Vc is about .7 km/sec.

Long-Term Environmental Degradation

Many one-shot tether applications involve only a few hours of exposure to the space environment, and Kevlar performs well after simulated exposure to those conditions. Long-term survivability in the space environment is not so clearcut an issue. Tethers will be exposed to six major insults:

1. Abrasion and crushing during reel winding
2. Collision with micrometeoroids
3. Temperature extremes and cycling
4. Ionizing radiation
5. Hard UV radiation
6. Energetic collision with reactive gas atoms and molecules.

1. In terrestrial applications, Kevlar seems to suffer slightly more from self-abrasion than many other fibers, so solid lubricants are often used in applications involving repeated winding and unwinding. This may be necessary also for repeated-use tethers in space. If winding Kevlar many layers deep under high tension causes crushing damage, then drive reels separate from the

storage reel might be required to reduce storage reel tensions. Use of large reel diameters could reduce both abrasion and crushing problems.

2. Impact tests with Kevlar indicate a sensitivity to micrometeoroids that is moderately greater than for equally strong steel tethers. This seems to be due merely to the lower mass of the Kevlar tether. Larger-diameter tethers can withstand larger collisions, and the impact frequency drops radically for larger micrometeoroids. As a result, more ambitious tether applications with heavier tethers will become inherently safer against micrometeoroids. This argument does not apply to the larger man-made objects in LEO, which can sever any size tether. Probabilities of catastrophic damage appear to be acceptably low for many applications.

3. Kevlar has good heat resistance for a polymer, retaining over 90% of its strength after prolonged exposure at 150C. This makes it practical for use down to altitudes of about 130 km. Kevlar loses a small amount of strength at very low temperatures, but it does not embrittle. It has a low coefficient of thermal expansion, so uneven heating should not cause any problems even in a pultruded composite structure. Thus its thermal behavior seems acceptable.

4. Kevlar has fairly good resistance to ionizing radiation, so at LEO altitudes, ionizing radiation damage should not be significant.

5. The most serious issues with Kevlar are UV radiation and chemical sensitivity. The polymer absorbs 90% of the radiation directed at it at 325 nm and 70% at 240. The exact effects of absorption are difficult to predict because of the polymeric nature of the material. Studies of UV degradation under terrestrial conditions are not necessarily representative, because the degradation pathway on earth involves singlet molecular oxygen, and this is a rare species in LEO. Suitable experiments with the proper airmass-zero solar UV spectrum should be performed in high vacuum in order to determine the long term effects of the radiation alone.

6. Possible degradation by exposure to high-energy gas atoms or molecules is the other major problem to be considered. At altitudes for long-term use, the most abundant reactive species is atomic oxygen. There are, however, many other gases present in considerable quantities which may become involved in degradation. With orbital impact velocities and simultaneous exposure to hard UV, the reactions are difficult to predict with confidence.

A preliminary "worst case" estimate for chemical damage may be made as follows. If only the atomic oxygen reacts, and each interaction between an oxygen atom and the tether results in cleavage of one molecule, and if (based on data from DuPont), a 20% reduction in average molecular weight cuts the strength in half, then the tether "half-life" will be 1-2 years at 300 km altitude. If the degradation is localized at the surface, with little damage to the bulk of the fiber, then the "half-life" could be much longer.

The short-term UV exposure tests Kevlar has passed have little relevance for longer exposures, and to date no experimental results are available on the sensitivity of Kevlar to atomic oxygen or to any of the other species present in LEO. Chemical experiments must be done, both in the presence and absence of UV, over the relevant range of temperatures, at various stress levels, with relevent abrading conditions, before Kevlar can be used with confidence in any critical long-term applications in space.

It is possible to avoid these problems entirely by jacketing the tether in a protective material and using lubricants. Without proper experiments, however, the optimum type and level of protection required is not known, and it is not even known whether a jacketed tether would be lighter than a bare tether that has an adequate safety margin for the intended use. Kevlar ropes in terrestrial applications provide effective self-screening, and this may hold in space as well.

Applications in which tethers are deployed only for rendezvous or release may call for different materials or construction than applications where they are continuously deployed: cutting the exposure time by a factor of hundreds reduces collision hazards and chemical degradation rates by the same factor, but also accelerates any physical degradation caused by reeling operations.

Tapered and Graduated-Property Tethers

Untapered Kevlar tethers become impractical for Vx-Vo much beyond the Vc of .7 km/sec, and a Gaussian bell-curve variation in tether cross-section is required. An attractive possibility for tethers with Vx-Vo beyond 1 km/sec is the use of several different materials for different parts of the tether.

The design logic is like that for staged rockets: mass reductions on an outer stage have effects that grow as they propagate to inner stages. Kevlar might be used out to 1 km/sec, and the small fraction of the overall tether mass beyond that point could be a much more expensive higher-Vc material with a more moderate taper than would otherwise be needed. Even a Kevlar-composite pultrusion might have higher usable Vc than straight Kevlar, and the reduced flexibility might be acceptable near the tip of a tether. Stepped construction might also be used with a refractory tip for access to lower altitudes where aerodynamic heating is too intense for Kevlar.

Composite technology is improving rapidly, and it is entirely possible that by the time ambitious tether applications fly, carbon-based composites or other materials might have significant advantages over Kevlar. Single-crystal specific strengths as high as 3200 km have been quoted for graphite, and even if only 10% of that were achievable in an affordable tether tip, it would have four times the usable specific strength of Kevlar, and hence twice the Vc.

G. ELECTRODYNAMICS OF TETHERS

The discussion so far has looked at the dynamics of orbiting tethers but has ignored the fact that they will be moving through a plasma in a magnetic field. For non-conducting tethers, the resulting electrodynamic effects are fairly minor, but electrodynamic effects on conducting (metal or graphite) tethers can be quite significant. This section describes some of these effects in an introductory way. Far more detail can be found in the references.

Any body in a plasma is necessarily surrounded by an electric field, and hence modifies its immediate surroundings. In the simplest case, the potential difference between the object and its surrounding is:

$$V = -kT/2e * \log(M/m)$$

where M/m is the ion/electron mass ratio and T is the electron temperature. This potential extends for about a debye length about the body, and inhibits electron collection by the surface while very slightly increasing the cross-section for ions. For very narrow objects, (<1 cm) this may increase drag somewhat.

If the body is exposed to sunlight, then UV induces a photoelectric current of electrons leaving the object. If no net current is to flow, then the potential must be modified to draw in an equivalent current. As a result. modest potential differences can occur over the surface of the body. If the body is conducting, either internally or externally, then currents will flow in the body. Then the current to the object need not be locally balanced, and currents may be induced in the plasma about the object. Such currents can interact with a magnetic field and increase drag.

If the body is in motion and in a magnetic field, then the fluxes of ions and electrons to the surface depend upon the orientation of the surface with respect to the field, and upon the direction of motion. (Electrons flow most easily along magnetic fields, while ion flux is greatest on the forward face.) These effects again lead to local variations in potential, or to internal and external currents, and hence again to possible modifications of the drag.

If a very large body (or a pair of bodies connected by a long tether) moves through a magnetic field, then there is a potential difference between top and bottom:

$$\Delta V = \underline{v} \times \underline{B} \cdot \underline{dl}$$

which is on the order of 200 volts/km. For tethers of many kilometers length this becomes substantial. If the tether is conducting then a substantial current can be drawn, determined essentially by the electron-collecting area at the top (which can be oriented in any direction, since the electrons move much faster than orbital velocity). If the tether is uninsulated or has a conducting surface, most of the current will flow into and out of the tether along its length.

On the other hand, for a conducting tether in an insulating jacket, the current may flow between the ends, and modest electrical power may be drawn. In that case, however, substantial electric potentials across the insulating layer appear, and may place considerable demands on the insulation. Current flowing in the tether interacts with the magnetic field and adds substantially to the drag.

If a tether draws a current, then the local value of the magnetic field is modified. How this happens depends on the way in which the current loop is closed, and on the velocity of the tethered system. If the tether is very short, then the return current will flow largely across the magnetic field lines and will form a more or less localized loop. However if the tether is longer than a few tens of kilometers, then current closure will be along the magnetic field lines and into the ionosphere, and a very large current loop will be formed. Since the speed of the tether system is much greater than sonic, but less than the Alfven speed, the magnetic field modification will form a nearly static pattern about the tethered system. This will produce changes in both the current that can be drawn and the drag effects.

Electrodynamics: Issues and a Possible Application

Some of the problems of the electrodynamic influences on conducting tethers seem close to being well understood (e.g., sheath formation), while some others, such as current closure, are problems unique to the tether in space. Some study has been given to those problems, but more work, both experimental and theoretical, should be carried out.

It is possible that kilowatts of electric power could be drawn from a properly-designed conducting tether system, and it is possible that this power might be drawn fairly efficiently from the orbital energy. If a space station with a momentum-transfer tether "steals" enough momentum from an orbiter at the end of a mission to drop the orbiter's perigee by 150 km, this transfers over 9000 kWh of orbital energy to the space station (and also saves 1.5 tons of OMS fuel). If this occurs once a month, and 20% of the energy is needed to overcome space station drag and the rest can be converted into electric power at 50% efficiency, then over 5 kilowatts might be drawn continuously.

It is even possible that—as suggested by Drell et al.—with a collecting surface at the bottom and power to force a current flow against the potential, a thrust might be produced at something approaching 50% efficiency. Such an Alfven engine or "orbital electric motor" might provide as much as a newton thrust for station-keeping, and might provide such thrust with less power than is needed by ion engines—and with no mass loss as in an ion engine. Cycling between motoring and power generation might circularize an eccentric orbit, or could be used to increase the electric energy storage capacity of a facility.

The potential output and efficiency of such devices is unknown. (Outputs of 5 kw to 65 kw are estimated for one generator design.) More research is clearly needed, but the potential usefulness, particularly in combination with massive momentum-transfer facilities, should make it worthwhile. The design constraints for the equipment itself seem to be fairly reasonable: adequate electrically-conducting surface at the electron-collecting end, and very good insulation (about 20 kilovolt) for the tether and hardware connected to it.

H. APPLICATIONS OF TETHERS TO ENHANCE STS & SPACE STATION CAPABILITIES

This section lists and describes a number of possible applications of tethers that can enhance STS and space station capabilities. The list is not comprehensive, but rather illustrative: a sampling of possibilities that have been proposed by Dr. Colombo or others. Candidates for early application are listed first.

1. De-orbiting the ET and boosting the orbiter
2. Lowering orbiter & boosting ET or payloads
3. Controlling ET drag to prolong orbital life
4. Adjusting the reentry zone of a decaying ET
5. Lowering orbiter, raising space station & payloads, generating power
6. Rendezvous with satellites, and debris collection
7. Orbiter rendezvous with space station
8. Applications for advanced-materials tethers

1. De-orbiting the ET and Boosting the Orbiter

Even in a scenario in which most ETs are taken into orbit and stored, there may be individual missions into orbits from which later recovery of an ET seems impractical. But taking the ET at least temporarily into orbit with the orbiter increases payload capacity (due to trajectory improvements and the specific impulse increase of the SSMEs over the OMS). Recovery and/or use of residual propellants (liquid and gas) can have even larger impacts. Finally, orbiting the ET can provide additional volume for payload (either in the inter-tank or in an external cargo carrier).

Three means of de-orbiting an ET seem feasible. One is to de-orbit the ET with the orbiter, then separate, and then reboost the orbiter either enough to stay in orbit or just to provide the desired reentry trajectories: into the Pacific for the ET, and to the desired landing field for the orbiter. A second method is to use a solid rocket and guidance package.

The third method uses a tether: not only to de-orbit the tank but also to boost the orbiter. Compared to simply abandoning the ET in low orbit, this actually increases payload capability, whereas the other methods cut payloads.

A tether might be stored and deployed in much the same way that guidance wires for a wire-guided missile are. An RCS burn could provide the initial separation velocity, and half an orbit or so later, another much longer burn would cancel out the separation velocity so the tether becomes taut without a large recoil. The process has thus created a pendulum, as shown in Figure 6a:

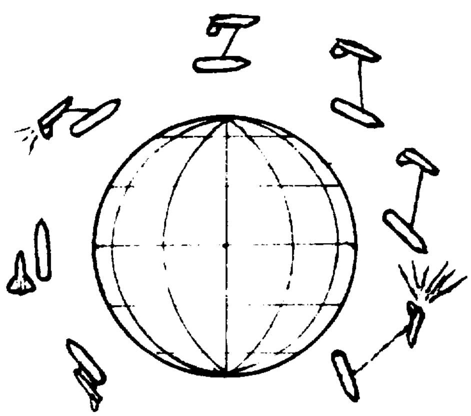

Figure 6a: Pendulum Setup

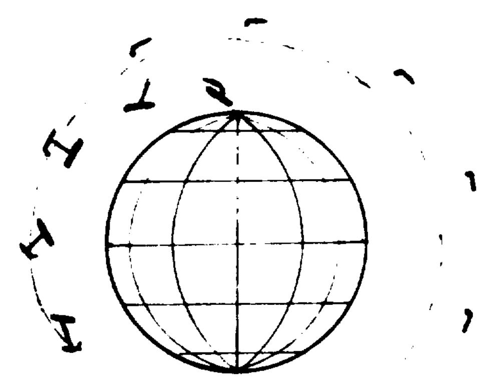

Figure 6b: Pendulum Swing & Release

Then the pendulum swings to the vertical and releases, starting the ET on a reentry trajectory and boosting the orbiter into a higher orbit, as shown in Figure 6b.

Assuming an unpressurized ET and reentry over the Pacific Ocean, tumbling may not be necessary to assure an adequately small footprint. If tumbling is still necessary, then some gas can be kept in the ET and the normal tumbling procedure used.

For this operation the required tether system mass should be on the order of 100 kg, and the fuel use required is about 300 kg. Assuming the other two methods of de-orbiting the tank have to leave the orbiter at the same altitude that the tether does, the other methods each require about 1000 kg mass.

Thus a tether system should increase payload capacity by about 600 kg (1300 lb). Such added payload capacity could be extremely valuable for high-inclination launches, when the STS is most mass-limited.

2. Lowering Orbiter while Boosting Payload or ET

This can be done in exactly the same way as de-orbiting an ET, except that the RCS/OMS burns are backwards rather than forwards, so the orbiter ends up at the bottom of the pendulum. The operation can reduce or even entirely eliminate any OMS de-orbit burn. If the full momentum change is useful at both ends of the tether, then tethers up to about 50 km long and weighing up to about 1600 kg can be justified. Such a tether could provide a 10 x 130 km decrease in orbiter altitude plus roughly a 40 x 560 km increase in altitude for an ET or payload. Maximum tether loads would be under 2 tons.

Dr. Colombo has done considerable work on the design and uses of a fully reusable tether deployer that, among other things, could do the same things as this disposable tether. That tether deployer is mentioned in Appendix II and is discussed more fully in several of the SAO reports.

3. Controlling ET Drag to Prolong Orbital Life

A particularly attractive use of tethers for stabilization is to store an ET in a minimum-drag orientation, rather than the (maximum drag) orientation that it would have by itself. Dr. Colombo has proposed this, and calculations in Appendix II indicate that it can quadruple ET orbital life.

An issue which has been raised in connection with this is the weakness of yaw restoring forces. However, as pointed out at the August workshop by Dr. Colombo, yaw librations in an orbiting (and hence rotating) system cause pitch librations which can be easily damped. Thus the main design constraint is to build adequate pitch libration damping into the system. This may not be too difficult, since perturbing torques at ET-storage altitudes near 500 km are much less than at the much lower altitudes used in most TSS simulations.

A final point related to small librations is that drag does not increase linearly with what might be called "projected shadow area" in the direction of motion. This is because random thermal motion of gas molecules at 500 km is equivalent to the ET having different orientations for different subsets of the total impacting population. Small yaw or pitch angles have effects on different subsets which nearly cancel out.

A gravity-gradient "kite" system used to reduce drag must have a fairly short tether to minimize the tether's contribution to overall drag. Most of the stabilization system mass will then be in the anchor. For stabilizing a tank, the total mass required seems to be on the order of half a ton.

Another means of quadrupling orbital life is simply to raise the orbital altitude about 80 km with a rocket. This requires roughly the same total mass investment. If the anchor mass in a gravity-gradient kite has no other use, then kites may have no advantage over rockets. However, if the anchor mass is a tether deployer, or a cache of supplies being stored for later use on a space station, then a gravity-gradient kite might be far better than a rocket.

4. Adjusting the Reentry Zone of a Decaying ET

An ET should not be stored in orbit unless it is planned to recover and use it before it reenters. However, in the event of loss of capabilities or a need to change plans, it is useful to have a backup means of adjusting the point of ET reentry, if it nears the end of its orbital life before recovery. A tether used for stabilization might also be used for this purpose.

It appears that an ET in decaying near-circular orbit will make its last complete orbit at an altitude near 150 km. This is well above the 120-130 km lower limit for Kevlar. Variations with the solar cycle affect both orbit and tether decay altitudes together, so an ET kite-tether should remain functional until the general impact region has already been determined.

However, at these low altitudes, differential aerodynamic drag may become as important as tidal effects. Thus the anchor of a kite tether could be in front of, in back of, or above/below the ET, depending on anchor and tether areas. At any rate, if ground control can adjust the kite bridle angle, then drag might be controllably varied over a range approaching 4:1. Using such controls over the last few days of the orbit may be enough to reliably limit the reentry footprint to a deserted region of the Pacific.

5. Lowering Orbiter, Raising Space Station & Payloads, Generating Power

The basic idea has already been mentioned earlier, and work in this area has been done by Dr. Colombo. Even if tether-mediated rendezvous techniques are not flight-ready, tether release techniques can be used to transfer energy and momentum from the orbiter to a space station.

If a release set-up similar to that described in application #1 is used to return the orbiter from a rather low space station altitude of 400 km, and the space station has three times the mass of the orbiter (perhaps mainly in the form of ETs cut up into shingles for shielding), then a 31 km tether of 2 ton mass is required. Maximum loads on the tether (and thus on station and orbiter) are under 3 tons, and occur just before release at the end of the pendulum swing. These peak loads could be reduced 35% by using a 2.5 ton hanging tether 60 km long, but deployment may take much longer.

Either version—swinging or hanging—can increase payload capacity by 3 tons, by eliminating the large OMS de-orbit burn needed for reentry from 400 km. The procedure also can provide enough momentum to a space station to eliminate any propellant use for overcoming long-term drag. The availability of such "free" momentum allows lower-altitude space station operations. (This is why 400 km was used for these calculations, whereas 500 km is assumed in much of the rest of the report.) A lower space station altitude has a further favorable impact on payload capacity to a space station.

Depending on the space station altitude and mission intervals, momentum in excess of drag make-up needs could pay for releasing payloads and ETs into higher orbits. Considerable research has been done at SAO under the direction of Dr. Colombo on a space-station tether facility for reducing the amount of propellants needed to deliver payloads to GEO and beyond.

If conducting tethers can efficiently generate electric power, as some investigators think possible. excess momentum might also be used to generate several kilowatts of electric power for months.

Any single release of an orbiter has an assymetrical effect on the space station orbit, but multiple flights can adjust their release points somewhat to help reduce this problem. Timely release of the ET (upwards or downwards), plus timely power generation with short-term storage if necessary, can reduce orbital eccentricity. Finally, sheer mass in the space station can allow not only more flexibility in scheduling operations but also the use of much lower space station altitudes. This is not only because of increased orbital life in a purely passive mode, but also because detachable masses could be released downwards to re-boost the station and further increase life.

6. Rendezvous with ETs and Satellites, and Debris Collection

Payloads and ETs placed into higher storage orbits by a space station or other tether deployer can also be recaptured with a tether. Since there will probably be more objects to capture than tether facilities, and since some of the objects to be collected may be uncooperative, the tether facility should have all the controls necessary to capture even a totally inert object.

An object to be captured must be in an orbit with the same inclination as that of the tether facility. In addition, their orbits have to be within one tether length in altitude at some point. Simply waiting allows differential regression of the nodes to line the planes up. Deploying tether days or weeks ahead of time can cause aerodynamic or electrodynamic drag to adjust orbital phase properly. Deploying the proper length of tether up or down adjusts the altitude of the tether tip.

A properly sized and phased pendulum swing can provide rough position and velocity matching between tether tip and object. Fine matching is then done at the last minute with thrusters at the tip of the tether (plus tether length adjustments if necessary). Because of the low mass of the tether tip, larger maneuvering delta-Vs and final docking adjustments are practical than when two massive objects rendezvous.

Such techniques can also be used to collect malfunctioning satellites. Such satellites can have unpredictable response characteristics, and are most safely captured at the end of a tether, well away from the expensive (and perhaps manned) main facility.

It may also be of value to collect large pieces of orbiting debris, when this does not conflict with other operations. If the debris is captured and then released into a reentry trajectory, some momentum can be recovered. If the object is retained, it can be used for momentum storage. In either case, the procedure helps solve an increasingly serious orbiting debris problem—particularly if the debris is collected before being fragmented by impact with other debris.

A final note here is that an orbiting ET can—unfortunately—be not only a debris sink, but also a debris source, if it collides with other objects. This problem should be investigated as part of any thorough study of the consequences of orbiting large numbers of ETs.

7. Orbiter Rendezvous with a Space Station

Tether-mediated rendezvous will probably be used with unmanned objects for some time to demonstrate safety and reliability. After this has been done adequately, tether-mediated rendezvous techniques can be used for rendezvous between orbiters and space stations. This can increase the payload capacity to a space station by at least 2 tons, by replacing the OMS burn that would raise the orbiter perigee to space station height. Appendix II goes into some detail on one means of rendezvous with a space station.

Here it will merely be mentioned that similar trajectories can also be used with centralized-mass space stations that have a bare tether hanging down from them. Such a space station might be considerably lighter than 15 ETs at first, but after 15 flights it could become the sort of two-platform station proposed by Dr. Colombo. Early in the construction phase, orbits during a mission (space station plus orbiter together) would not be much higher than the orbiter transfer trajectory, but this is high enough for short missions.

At the end of the mission, a hanging or swinging release can recover more momentum from the orbiter than was lent to it at rendezvous. For example, an orbiter in a 200 x 370 km transfer orbit might rendezvous with the lower end of a 30 km tether hanging down from a space station at 400 km. At the end of the mission, the same tether can swing and release the orbiter into a 50 x 370 km reentry trajectory. The 150 km change in orbiter perigee equals a 9000 kwh increase in space station energy. This energy can be used for electric power, drag makeup, and ET or payload boosting in any combination. The overall OMS savings on such a mission might also allow payload increases of over 5 tons.

8. Applications for Advanced-Materials Tethers

If tether materials with much higher usable specific strength than Kevlar become available, then considerably longer tethers may become practical. Such tethers (perhaps together with mass provided by ETs) might make possible some of the following:

a. Apparent gravity of .1 gee or more for personnel throughout a mission;
b. Launch delta-Vs low enough for "single-stage-to-tether" vehicles;
c. Reentry velocities low enough for hot-structure reentry vehicles;
d. Release of payloads from LEO into GEO transfer orbits without rockets;
e. Tether-based transportation between lunar surface, orbit, and escape.

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IV. UTILIZATION OF TANK MATERIALS

A. Group Recommendations

B. Materials Available in the External Tank (ET)

C. Potential Products Producible from ET Materials

D. Space Manufacturing Processes for

1. Production of Raw Stock
2. Fabrication of Products

E. Power Requirements for Space Processing

1. Melting, Evaporation, Flake or Wire Production
2. Chemical Processing

F. Recommended Initial Materials Experiments

G. Long Range Materials Processing and Manufacturing Activities

A. Group Recommendations

1. The hydrogen and oxygen tanks of the ET can be used as workshops in space for materials processing, manufacture, testing and storage.

2. External tank materials provide an important resource. The abundant aluminum alloys can be converted to flakes, wire, sheet, film, castings and structural elements to form parts and components useful in space. Other useful engineering materials available in the ET in lesser quantities can be similarly processed.

3. Many parts of the ET may be salvaged for re-use in other capacities. Considerable quantities of metals and plastics may be removed from both the inside and outside of the ET and further processed without it sacrificing its use as a pressure vessel, testbed or strongback.

4. The external tank should be fitted with standard 36" diameter access ports in place of the present manhole covers to permit the entry in orbit of astronauts and equipment transferred from the Shuttle orbiter.

5. Hydrogen and oxygen propellants should be recovered and stored in superinsulated tanks for future use as propellants, for energy generation and as a source of water.

6. A number of materials processes experiments are recommended for early conduct inside the ET. These include:

   a. Production of aluminum alloy powder or flake suitable for use as a rocket propellant and as material for the manufacture of products by powder metallurgy techniques.

   b. Production of thin aluminum alloy sheet or film suitable for the fabrication of components such as solar concentrators, superinsulation, antennas, solar sails, and thermal radiators. Several candidate processes and types of equipment are readily available for this activity.

   Power for the conduct of the above experiments may be furnished by a number of means including H_2-O_2 fuel cells or solar concentrators.

B. Materials Available in the External Tank (ET)

The components of the ET consist of the structural and other elements listed below. The description and weights of these elements were taken from the report resulting from the Workshop on Utilization of the External Tanks of the Space Transportation System, held at the University of California at San Diego on 8-9 March 1982[1].

Component	Weight, lbs.	% of Dry Weight
Forward Tank (LOX)	12,352	17.9
Intertank Structure	12,080	17.5
Aft Tank (LH_2)	28,900	41.9
Insulation	6,190	8.94
Separation Hardware	4,743	6.86
Propulsion Lines	3,760	5.45
Miscellaneous	1,000	1.45
Total	69,025	100.00

Data extracted from a Martin-Marietta mass properties report (Table I) show the total weight of the external tank to be approximately 67,900 lbs. This 1,100 lb difference is due in part to the fact that quantities of materials other than those listed in Table I are also used in the ET. Included are a number of A356 aluminum alloy castings and some small quantities of the wrought 6063 and 7050 aluminum alloys. Other materials not listed in Table I are Teflon insulation on electrical wiring, small rivets and fasteners (not A286 stainless steel) used in the intertank structure, glass phenolic thermal separation pads and limited quantities of several different urethane foam insulation materials. The nickel base alloy Inconel 718 is used in numerous applications such as springs, spindles, monoballs and other interface fittings. The chemical compositions of the major metallic materials used in the ET are listed in Table II.

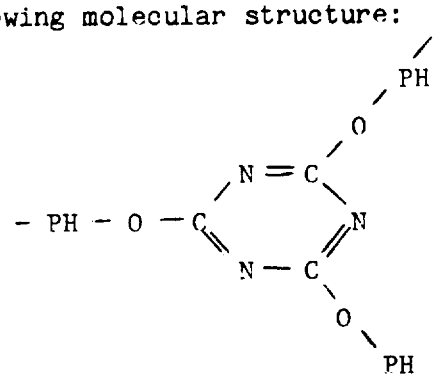
As shown in Table I, aluminum alloys comprise almost 85% of the dry weight of the external tank.

The stainless steels are used for major portions of the large-diameter propellant feed lines, and for the considerably smaller-diameter helium, gaseous oxygen and gaseous hydrogen pressurization and venting lines, as well as for lines and components used for other purposes. The titanium - 6A1-4V alloy is used in the form of castings and forgings as attachments and interface hardware components.

The thermal protection system consists of foam insulation applied over the surfaces of the liquid oxygen and liquid hydrogen tanks of the ET and a high-temperature ablator material applied to areas subjected to more severe aerodynamic heating during the Shuttle launch phase.

Table I gives a total weight of foam and ablator insulation materials of 5,630 lbs., which is 560 lbs. less than the amount given at the 8-9 March 1982 Workshop. This decrease in insulation weight probably resulted from Shuttle launch experience which demonstrated that the topcoat which was originally applied over the "as-sprayed" foam insulation could be eliminated without deleterious effect.

The foam insulation consists primarily of a polyisocyanurate, fluorocarbon (CPR 488) blown, closed cell, rigid-foam system. The material is compatible with the cryogenic tanks and is stable at substrate temperatures up to +300°F. Its as-sprayed density is 2.4 lbs. per ft.^{3} and it has a very low thermal conductivity, particularly at very low temperatures. Isocyanurate has the following molecular structure:



PH = Phenyl group

Polyisocyanurate contains 60% by weight carbon, 20% oxygen, 17.5% nitrogen and 2.5% hydrogen.

This foam insulation is from 1" to 2" thick along the ogive of the LOX tank, and 1" thick over the bulk of the area of the hydrogen tank.

In addition to the far more extensively used polyisocyanurate foam insulation, two urethane foam insulations, designated BX-250-2 and PDL-4034-3 are used on areas where hand pouring is more suitable for foam application or where difficult shape cavities must be filled. Both of these urethane insulations are closed-cell rigid foams. Their overall characteristics and properties are similar to those of the CPR-488 material, but are limited to +200°F substrate temperatures.

The ablator material consists of a mixture of silicone resins highly filled with cork particles, silica glass ecospheres, phenolic microballoons and silica fibers. The ablator material is sprayed in a slurry with heptane on a surface which is previously primed and coated with an adhesive. The ablator has a density of 18 lbs. per ft.^{3} and a fairly low thermal conductivity. The silicone ablator, designated SLA-561 is generally applied in thicknesses ranging from 0.15" to 0.35". In some special areas exposed to critical aerodynamic heating, the ablator may be as much as 0.65" thick, but these areas are very limited in size, and consist of 37.8% by weight of silicon, 32.4% carbon, 21.6% oxygen and 8.1% hydrogen.

In some limited locations where a higher performance ablator is needed, the SLA-561 is modified by deleting the cork and phenolic microballoon fillers to achieve a density of 30 lbs. per ft.^{3} When so modified, the ablator material is designated MA-25S.

A breakdown of the elemental content of the ET is shown in Table III. Aluminum is by far the most prevalent element. Copper is next, 4.6% represents the copper content of the aluminum alloys and approximately 0.4% the essentially pure copper in the electrical wiring. The actual carbon content is somewhat higher because of the cork filler in the ablator, but the exact amount is unknown. The elemental composition of the ablator was calculated from that of the silicone resin and ignored the cork, phenolic, glass and silica fiber fillers since the contents of these are unknown. The resulting errors are for all practical purposes negligible.

Examination of the design of the ET shows that considerable amounts of metallic and nonmetallic materials can be removed without loss of pressure tightness of either the liquid oxygen or liquid hydrogen tanks. If either or both of these tanks are to be used as space habitats, work stations, rescue, repair or propellant storage facilities in space, which require pressure tightness, significant amounts of aluminum alloy could be obtained from the anti-slosh and vortex baffles, interface hardware and propellant lines without hindering the pressure vessel resource. These components permit materials experiments and processing studies to be performed in space. Similarly, stainless steels, Inconel 718, copper, and the Ti-6A1-4V titanium alloy could be obtained from pipes, tubing, interface hardware attachments and electrical lines. Since insulation requirements for long term space storage of cryogenic propellants are radically different from earth launch insulation requirements, the foam and ablator materials can also be removed from the tanks and used for space materials R&D if such proved desirable.

In addition to the basic tank materials, liquid hydrogen and liquid oxygen propellants remain in the tanks after separation from the Space Shuttle orbiter vehicle. Depending on the specific Shuttle payloads and launch trajectories, the amount of residual cryogenic propellants may be in the range of 10,000 to 40,000 lbs. A significant factor in using the ET for various scientific and engineering purposes is the recovery and use of the propellants. The recovery of the propellants while they are still liquid must be done soon after ET separation from the orbiter.

The propellants must be transferred to tanks covered with superinsulation that would keep them liquid for weeks without further refrigeration. They can then be used for a variety of purposes; as propellants for other space missions, or for energy production in fuel cells or turbines (resulting in the formation of water which is also needed for in-space materials processing and manufacture). Hydrogen and oxygen may be used in various chemical processes involved in metals and plastics treatments. Stored cryogens may be useful in pre-cooling of systems requiring cold operating conditions.

Consideration should also be given to recovery of the OMS propellants and storage in tanks attached to the orbiting ET's. Having OMS propellants available in space could be very important in permitting extension of Space Shuttle orbiter activities to perform additional missions before returning to Earth. This would be of particular value to military missions.

C. Potential Products Producible from ET Materials

There are a number of products which, if they could be produced in an Earth-orbiting manufacturing facility, would materially increase both the potential for, and efficiency of, space operations. The production of propellants, spacecraft components, and power sources in such a facility might open up opportunities for lunar, asteroidal, and planetary exploration. Starting out into space from an orbiting station circumvents climbing out of the deep gravitational well we now occupy on the surface of the Earth.

Since aluminum amounts to 78.5% of the total dry weight of the ET, the most likely potential products to be made from the ET would use this metal. Aluminum and aluminum alloys, when converted into suitable forms, can be used as space vehicle propellants, as parts and structural elements of Earth orbit-to-space vehicles, as mirrors or reflectors for solar heating and melting devices, as antennas for space communication and as solar sails for passive space vehicles. Multilayer aluminum foil with each layer separated from adjacent layers by very small staggered pieces of foam insulation cemented to one side of each foil layer provides superinsulation for long term storage of cryogenic propellants in the vacuum of space.

Aluminum, as well as other ET derived materials, may be pressed into use as micrometeoroid and solar radiation shielding for a manned space station or workshop facility. While low molecular weight materials do not provide efficient radiation shielding, enough thickness of even aluminum can be accumulated to provide the necessary shielding for long term habitation of an orbiting space station (see section VIII). With many ET's ultimately available in orbit, sufficient amounts of aluminum will be available for this purpose.

Aluminum can also be used for materials science studies. Research studies which may be performed with aluminum and aluminum alloys include experiments on immiscible alloy systems, dispersion hardened alloys, on large single crystals of pure metals and single phase solid solution alloys, on eutectic alloy systems and on fiber reinforced metals.

Stainless steel, nickel and titanium alloys disassembled from ET hardware can be made into powder for powder metallurgy parts fabrication, can be melted and made into castings and can be vapor deposited to form thin sheet and plate material.

As will be discussed later, the foam insulation and ablator materials can be processed to extract useful elements and compounds.

Under a study performed for the NASA Johnson Space Center on the topic of Lunar Resources Utilization for Space Construction* the General Dynamics Convair Division investigated the potential of the aluminum-oxygen propellant system to power space station-to-lunar transport vehicles.[2] This study concluded that an Al-LOX propulsion system could generate a specific impulse, I_{sp}, of 255–265 seconds. This compares to the I_{sp} of 280 seconds for the JP4-LOX propellants used in the Atlas booster vehicle and the I_{sp} of 450 seconds for the LH_2-LOX engines of the Centaur space launch vehicle. The alumninum fuel was conveived to be a fine powder that is fed by a spiral screw mechanism into a fluidizer where it is mixed with gaseous oxygen before entering the thrust chamber into which liquid oxygen is being pumped.

Aluminum and aluminum alloy powder can be produced by conventional as well as non-conventional powder metallurgy techniques. Castings can be made by a variety of melting techniques and centrifugal casting to insure the filling of molds. Metal films and foils may be produced by electron beams, sputtering, lasers and ion plating techniques, some of which have already been demonstrated in space and in zero-gravity experiments.

While engines, pumps, valves, electronic equipment and other high precision components for Earth orbiting station, lunar, asteroidal or planetary use would probably have to be supplied from Earth, it would be possible to manufacture the core structure, tanks and cargo pods for interspace vehicles in an Earth orbiting space manufacturing facility, using ET-derived materials. Long beams could be readily cut from the cylindrical sides of the liquid hydrogen tank, propellant lines and electrical systems and wiring, taken from the ET and some of the interface hardware, could possibly be directly incorporated into interspace vehicles.

The manufacture of spacecraft or major components thereof from ET materials is, however, a distant prospect. Of more immediate concern is the demonstration that practical processes can be applied to transform ET derived materials into useful raw stock from which a variety of products can be made or which can be used for scientific experiments to advance materials knowledge.

In summary, a large number of potential products may be made from ET derived materials. These include:

1. Aluminum metal flakes for use as rocket fuel.
2. Aluminum foil or film for use as:
    a. solar concentrators
    b. antennas
    c. superinsulation

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*Contract NAS9-15560

d. thermal radiators

e. solar sails

3. Aluminum, stainless steel, nickel and titanium alloy flakes or wire for manufacture of powder metallurgy parts.

4. Aluminum, stainless steel, nickel and titanium alloy castings.

5. New alloy systems, large single crystals, dispersion hardened alloys and new composites made under zero-gravity conditions.

6. Hydrogen, oxygen, water and other useful elements and compounds extracted from the ET insulation and ablator materials.

7. Micrometeoroid and radiation shielding.

8. High purity silicon for solar cells.

9. Aluminum alloy structural parts; beams, girders, trusses, pressure vessels, etc.

D. <u>Space Manufacturing Processes For</u>:

1. <u>Production of Raw Stock</u>

Considering that the near-Earth solar heat flux amounts to 1.35 kw/m^2, an early step toward processing ET materials would undoubtedly be the construction of large solar concentrators to be used for heating and melting purposes. Aluminum or aluminum alloy sheet formed into polished parabolic shells or aluminum vapor deposited on plastic film which can be shaped into the proper configuration would make efficient solar concentrators.

Powder metals can be produced by a number of conventional processes, including the rotating electrode process, atomization by means of liquid falling on a rapidly rotating disc, by vacuum atomization and by centrifugal shot casting. All of these processes are currently used to commercially produce metal powders, and at least three of the above processes do not depend upon gravity to cause the molten material to fall upon a rotating disc when the molten stream is atomized. Several years ago, a novel method of producing fine metal flakes and wire was developed at the Battelle-Columbus Laboratories.[3] This process involves a rapidly rotating notched or smooth metal disc with a wedge-shaped edge slightly immersed in a molten bath of metal. The edge of the disc picks up a thin stream of metal which becomes solidified and thrown off from the rotating disc. A fiberglass wiper wheel in contact with the edge of the disc keeps it clean, see Figure 1. This method of metal flake and wire production is called the "Crucible Melt Extraction (CME)" process. As developed, the metal is melted in an induction or resistance heated crucible.

This process can be readily adapted to a zero-gravity environment as shown in Figure 1a. An electron beam gun or solar concentrator can melt a portion of bar stock or other moderately large section of metal, and the molten mass would attempt to form a near spherical shape and be held in place between the two solid sections by means of surface tension.[4]

A modification of the CME process, called the Pendant Drop Melt Extraction (PDME) process was also developed at the Battelle-Columbus Laboratories.[3] The disc designs, speed ranges, control of fiber shapes and method of collection of flakes or filament are exactly similar to the CME process. The major difference is that the end of a vertically positioned wire is melted by an electron beam. Surface tension causes the molten droplet to remain attached to the wire, and the disc rotating in contact with the droplet wipes it away to form the flakes or wire (see Figure 2). The finely focused electron beam provides continuous melting of the end of the wire. The PDME process has shown the capability of producing finer fibers and continuous filaments of metal in the range of 0.001"-0.005" in diameter. The CME produces somewhat larger diameter filaments. Both the PDME and CME processes are ideally suited for both a zero-gravity and vacuum environment since no contaminants or oxides can interfere on the surface of the molten droplets or sphere.

As seen above, electron beam equipment as well as solar concentrators can play an important role in space materials processing. Both can also be effectively used in materials science research on fundamental investigations of metal solidification, dendrite growth, phase transformations and the various effects of zero-gravity on these and other phenomena. Electron beam equipment can also be used for vapor deposition of aluminum on metal and plastic film surfaces for the manufacture of solar concentrators and on thin films for use as large solar sails. Techniques are available for dissolving the plastic film, leaving very thin, lightweight aluminum films for the sail material.

Processing of metals and manufacture of parts and components need not, of course, be confined to aluminum and aluminum alloys. A-286 bolts and nuts can be disassembled from interface hardware components and melted to form large pieces by using solar concentrators or electron beam equipment. The same can be done with the Inconel 718, stainless steel and titanium alloy parts. Electron beam and laser equipment can be used for melting, cutting and shaping of metal pieces. Laser machining is an already established process. All of the forementioned alloys can also be reduced to metal flakes and wire by the PDME and CME processes.

As shown in Table I, each ET is covered with approximately 2 tons of foam insulation and three-quarters of a ton of silicone-based ablator materials. The bulk of these materials can be stripped off the ET surfaces and processed for recovery of their chemical and elemental constituents. Heating of the polyisocyanurate foam insulation to temperatures in the range of 400-600°F will cause its decomposition, releasing hydrogen cyanide (HCN), free nitrogen, carbon monoxide and dioxide and a complex carbonaceous char. Processing these products further to extract useful elements and compounds would require a moderately large amount of equipment such as flasks, reactors, retorts, glassware, etc. and several chemical reactants, all of which must be transported from Earth. Processing of the insulation is therefore not recommended at an early stage.

The same holds true for the ablator materials, although at a later stage of processing materials in space, very useful products can be extracted from the ablators. Heating the ablator material to 500°F and above will result in its decomposition to silane trimers and tetramers along with methane, ethylene and other hydrocarbons as well as a considerable amount of char material. Since the production of silane is one step in the manufacture of high purity silicon for photoelectric cells, future production of photoelectric cell grade silicon from ET ablator materials may be worth considering.

The silicone binder in the ablator has 8.1% by weight hydrogen. An interesting possibility is provided by exposing this material to radiation which occurs in space. The result is the release of molecular hydrogen.

2. Fabrication of Products

As the first step in producing useful products from ET materials, it would be highly desirable to fabricate solar concentrators to be used in subsequent processing involving high heat inputs. While the ET tanks and intertank structure contain very large surface areas of moderately thin aluminum alloy sheet and machined plate, most of it is either heat treated or heat treated and coldworked to high strength levels such that it cannot be further formed into the paraboloid curvature necessary to make efficient solar concentrators. Furthermore much of the tank areas are machined from thick plate such that T-shaped stiffeners are integrally formed on the inner surfaces of the tanks, along with thickened areas at weld lands. Very irregular surfaces would result if an attempt were made to form such pieces into the shape of a reflector.

The portion of the ET that would come nearest to being useful to form into solar concentrators is the intertank skin, which is made from relatively thin 2024-T81 sheet to which longitudinal stringers and transverse rings are mechanically fastened. Once the ET is in orbit, the intertank structure holds the liquid oxygen and hydrogen tanks together in a stress-free condition. Large areas can be cut out from the skin of the intertank structure without creating structural problems or affecting the leak tightness of the propellant tanks. The stringers and rings can be readily detached by removing the fasteners, leaving smooth curved sections of uniform thickness with small regularly spaced fastener holes which would not seriously detract from the reflecting ability of a properly shaped and polished solar concentrator. However, the 2024 aluminum alloy does not have sufficient ductility in the -T81 condition to be readily formed into a parabolic section. The -T81 temper results in high strength and low ductility.

In view of the above, solar concentrators could best be made by some deposition process such as electron beam evaporation or sputtering of aluminum onto a substrate material such as plastic film. Vacuum deposition processes have been widely evaluated for thin film application to solar energy.[5] Sputtering is claimed to provide more uniform deposition over larger surface areas than is possible with electron beam evaporation, and this process is presently being used commercially to form reflectors and mirrors. The use of magnetron-type sputtering allows the deposition of aluminum on temperature sensitive substrates such as plastic films.

Very light-weight packageable metal mesh and metal foil antennas have been developed, some of which when unfurled are of very considerable size. Therefore the choice is available to carry similar packageable solar concentrators with aluminized film reflecting surfaces in either the Shuttle payload bay or an aft cargo carrier (ACC), or to fabricate them from ET materials. The latter can be done by sputtering or electron beam deposition of aluminum on plastic film and then constructing large solar concentrators by suitable arrangement of flat panels of aluminized film stretched over grids of aluminum sheet cut from the intertank structure. In the latter case, sputtering and electron beam equipment, supporting power supplies, plastic film and associated facilities must also be brought up from Earth. In any case, these types of equipment should be available for other product manufacturing processes involving ET materials.

Electron beam evaporation is widely used in terrestrial industries.[6,7,8] Electron beam guns are energy efficient and can be used for continuous metal vaporization in a continuous process.[9,10] In the Libbey-Owens-Ford Co. where glass is coated with a thin metal film, "the guns operate for over a year before requiring maintenance."[11] Accurate control of the electron beam permits controlled vaporization of aluminum from either a solid piece or molten pool of metal.

K. E. Drexler suggests that very thin unsupported films, 15-100 nanometers in thickness, are suitable for in-space manufacture of solar sails.[12] Deposition of films of these thicknesses on a substrate is within current technology. Physical separation of the metal film from the substrate is out of the question.[13] Current terrestrial methods imply a parting agent applied between the substrate and the metal film. This may be a soap film created by dipping the substrate or a vapor deposited salt or organic dye. The aluminum film is deposited in top of the parting agent, then a liquid solvent is used to release the foil. In space manufacturing, this parting layer could be sublimed through pin holes pierced into the film. The parting agent can then be collected and reused.

A method for the continuous production of a 10,000Å (1000nm) film of aluminum has been developed, using a continuous copper ribbon as the substrate.[8] The combination of a somewhat thicker aluminum film and the polished flexible copper surface allows physical separation by stripping the aluminum off the copper as shown in Figure 3.[14,15] The processes described for producing unsupported films have the distinct advantage of minimizing the amount of Earth-supplied materials since the substrates and/or parting agents are recycled, not used up. As was previously described, superinsulation for long term storage of cryogenic propellants in the ET tanks can be made in the same manner as the aluminized plastic film fabricated for solar reflectors, sails and antennas. The spaced multilayer array of aluminized film composing the superinsulation is made by adhesively bonding staggered dot-like pieces of foam prepared from the available ET insulation to one side of each film layer. A simple, light-weight proprietary machine has been developed for this purpose at the General Dynamics Convair Division.

Aluminum powder for use as a propellant may be made from the anti-slosh baffles in the ET LOX tank, from aluminum alloy interface hardware, the solid rocket beam (SRB) in the intertank structure, etc. The previously described Battelle PDME or CME processes are suitable for the manufacture of aluminum and other alloy powders, using either solar concentrators or electron beam equipment to melt the metal. Aluminum alloy, stainless steel, nickel and titanium alloy powder made by these processes can also be used to fabricate parts by powder metallurgy techniques, using some of the processes described by D. R. Criswell[16] as being suitable for in-space manufacture.

With respect to the production of new alloys, composite materials, large single crystals, etc., it will be first necessary to conduct research and development studies to determine which, if any, justify being manufactured in space. Many of the critical experiments pertinent to the above have already been planned for execution in the European Space Agency's Spacelab. A total of 39 materials science experiments on crystal growth, metallurgy, fluid physics, etc. are planned for Spacelab 1.[17,18,19] The results of these and other materials-oriented space experiments will strongly influence what will later be done with ET materials.

Solar heat is available in space at high and constant intensity (1.3 Kw/meter^2). It seems interesting to consider what can be done to create useful products using this capability. Figure 4 shows a conceptional design for a concentration-solar furnace in an External Tank, intended to generate large quantities of fused, clean Al_2O_3. We believe that this material, synthesized from aluminum and oxygen, has a potential market on earth for laser rods, other technical applications and perhaps also as synthetic gem sapphire and ruby. The scale of the concentrator is about equal to that of the tank, and it has other potential applications. Other interesting high temperature materials might be made in quantity, such as TiO_2, carbides, and others.

The special attributes of the External Tank which are useful here are (1) its large dimensions, which make collectors of long focal length easy to mount (such collectors are much easier to make, being nearly flat, and have deep focal zones), and (2) the large wall area of the tank, which makes it an excellent radiator to dump waste heat. These advantages could otherwise only be realized by an expensive dedicated facility.

E. Power Requirements for Space Processing

1. Melting, Evaporation, Flake or Wire Production

The energy required to heat one gram atomic weight of aluminum (27 grams) from the ambient temperature to its melting point is approximately 4.2 Kcal. or 17.6 Kjoules; and an additional energy of 2.5 Kcal. or 10.5 Kjoules is required to melt it. The sum of 28.1 Kjoules per gram atomic weight converts to 1.04 Kj per gram or 1.04×10^9 joules per metric ton to heat and melt aluminum.

The entire structure of the external tank contains approximately 25 metric tons of aluminum which would require roughly 26×10^9 joules (7200 Kwh) for complete melting. A minimal solar thermal power plant compatible with the requirement for complete melting of the ET might utilize a solar concentrator having a diameter equal to that of the ET (8.25 m). The projected end area is approximately 52 m^2 which will intercept 70 Kw of solar radiation. Assuming a 50% thermal efficiency (this is excessively conservative) for a solar concentrator at approximately 1000°K, a net power of 35 Kw is available; sufficient to melt all of the aluminum in an ET in 206 sunlit hours, assuming no thermal exchange between input and output streams.

An efficiency of 70% is more likely for a solar concentrator in a near Earth orbit, so that one having a diameter of 8.52 meters will probably provide up to 50 Kw of power, much more than sufficient to initiate or demonstrate an inspace materials processing capability.

High density packaged large, unfurlable antennas have been developed. One need only provide a highly reflective aluminized film to such a device to have an efficient solar concentrator.

Electrical power would also be needed to illuminate the interior of the workshop tank or tanks, to operate general machinery, electron beam and sputtering equipment, etc. It is estimated that less than 20% of the primary thermal power, or approximately 10 Kw would be sufficient. This power could be provided by an H_2-O_2 fuel cell consuming approximately 10 Kg per hour of the stored propellants.

The rejection of furnace heat can easily be accomplished within the shadow envelope of the solar concentrator. The same projected area (52 m^2) can reject the full input power of 70 Kw at 403°K if the surface emmissivity is 0.9. Any lower temperature heat rejection required may be done passively in the shadow region. Heat may be radiated either directly from products (ex., warm ingots) or by passive systems.

2. Chemical Processing

At a later and more sophisticated stage of conversion of ET derived materials to a wider range of physical and chemical products it may be desirable to increase the power available within the ET Workshop. For example, while metallic aluminum powder or flake provides a reasonably good fuel for rocket propulsion, aluminum hydride, AlH_3 would be a considerably more energetic fuel and would provide a higher specific impulse. Also, extraction of various elements from the ET alloys would require electrochemical processes requiring up to 30-40 times the power required for melting operations. This would require a space electrical power plant in the range of 300-400 Kw capacity.

Among the processes which may be considered in the future is the chemical conversion of the cryogenic propellants to storable propellants. Hydrogen and oxygen can be stored in space for reasonably long times with minimal losses (months) in superinsulated tanks. This requires, however, removal of the residual liquid cryogens from the ET's within minutes of their going into orbit and very rapid transfer to the superinsulated tanks. Significant losses of propellants may result.

The capital equipment, mass and power requirements for the conversion of hydrogen and oxygen to storable compounds are inversely proportional to the processing rates. If one is willing to extend the manufacturing rate to approximately one month, the amount of chemical reagents, solvents and processing equipment may, in most cases, represent a small fraction of the mass of the hydrogen and oxygen processed.

Furthermore, the manufacturing facility can be saved and used on subsequently launched ET's with only slight replacement of reagents lost in process attrition. Among the possible storable fuels which may be manufactured are

NH_3, N_2H_4, AlH_3, $LiAlH_4$, Si_2H_6. Storable oxidizers include H_2O_2 or, as monopropellant, $C(NO_2)_4$.

F. Recommended Initial Materials Experiments

Since aluminum powder (flake) has ubiquitous uses as propellant fuel, and as starting material for powder metallurgy processes, its manufacture is recommended as one of the initial practical demonstrations of ET materials usage. The production of aluminum particles may be achieved by any of the processes described in earlier sections of this report; i.e. by the Battelle-Columbus Laboratories PDME or CME methods or by vacuum or gaseous atomization. These are established technologies with well known equipment and power requirements.

Another early materials processing demonstration involves the production of aluminum film or sheet for use as solar concentrators, solar sails, super-insulation or thermal radiators. Deposition of aluminum on plastic film or on a polished copper endless belt from which it can be stripped may be done by electron beam evaporation or sputtering processes, all of which are established technologies.

Thin film aluminum alloy may be deposited on mylar or Teflon film by means of electron beam evaporation on sputtering to provide highly reflective film for fabrication of solar concentrators or antennas. Unsupported aluminum alloy film may be fabricated by using a parting agent on a reusable substrate and then subliming the parting agent after deposition of the aluminum.

Thicker aluminum alloy sheet deposited upon and stripped from an endless copper belt may be converted into large pieces by cold pressure welding overlapping edges together. Little pressure is needed since clean, unoxidized metal surfaces readily weld together.

The demonstration of the above two processes; i.e. converting ET materials to aluminum alloy flakes and sheet or film provides the proof of a useful in-space materials processing capability. From these starting materials, many products required for man's activities in space can be manufactured.

With the provision of standard 36" access ports in place of the end covers on the ET tanks, Astronaut workcrews, power supplies and equipment can be transferred from the Shuttle to the interior of the tanks.

G. Long Range Materials Processing and Manufacturing Activities

The recommended initial ET materials processing experiments involve only the aluminum alloys which represent 85% of its dry weight. As shown in Tables II and III, significant amounts of 13 elements other than aluminum are available in the ET. It may be assumed that an advanced materials processing facility would be able to recover or otherwise utilize most if not all of the available elements in the form of high purity elements, compounds and components. This advanced materials processing and manufacturing facility would be able to fabricate thin-film photovoltaic converters with 5-9% energy conversion efficiency, as well as a large variety of products. Table IV lists various materials and product opportunities that could ultimately be developed to fully utilize the materials in space offered by the ET.

Often the payload capacity of the Shuttle will be volume rather than weight limited. Dense materials such as iron, titanium, nickel, carbon, etc., could be shipped up and combined with ET-derived materials to considerably widen the range of engineering materials available in orbit. For example, a wider variety of aluminum alloys could be provided in space than are available in the ET.

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Table I

Estimated ET Materials Breakdown*

Aluminum Alloys		57,290 lbs.
1100	20 lbs.	
2024	8,730 lbs.	
2219	42,220 lbs.	
6061	40 lbs.	
7075	6,280 lbs.	
Iron and Nickel Base Alloys		1,370 lbs.
Stainless steel	1,180 lbs.	
Inconel 718	190 lbs.	
Titanium Alloy		440 lbs.
Ti-6A1-4V		
Foam Insulation		4,050 lbs.
Ablator Material		1,580 lbs.
Copper (Primarily electrical wiring)		300 lbs.
Miscellaneous (Std. parts, seals, GFE Components, etc.)		2,842 lbs.
	Total	67,872 lbs.

*Data from Martin-Marietta report MMC-ET-SE02-76, Mass Properties Status Report.

Table II

Chemical Compositions of Metals in the External Tank

Weight percent composition (nominal)

Aluminum Alloys	Al	Cu	Si	Mg	Zn	Mn	Other
1100	99.0 min.	0.12	-	-	-	-	----------
2024	93.5	4.4	-	1.5	-	0.6	----------
2219	93.0	6.3	-	-	-	0.3	0.6Ti, 0.10V, 0.18Zr
6061	97.9	0.3	0.6	1.0	-	-	0.2 Cr
7075	90.0	1.6	-	2.5	5.6	-	0.25 Cr

Iron & Nickel Base Alloys	Fe	Cr	Ni	Mo	Mn	Si	C	Other
304L	Bal.	19.0	10.0	-	2.0	1.0	0.03 max.	----------
321	Bal.	18.0	10.5	-	2.0	1.0	0.08	5x%C min Ti
347	Bal.	18.0	11.0	-	2.0	1.0	0.08	10x% min Nb+Ta
A-286	55.2	15.0	26.0	1.25	-	-	0.04	2.0 Ti, 0.3V, 0.2 Al,0.005B
21-6-9	Bal.	20.25	6.5	-	9.0	-	0.04 max.	0.30N
PH 13-8 Mo	Bal.	12.5	8.0	2.25	-	-	0.05	1.1 Al
Inconel 718	18.5	19.0	52.5	3.0	-	-	0.08 max.	5.1 Nb, 0.9 Ti 0.5 Al, 0.15 max Cu

Titanium Alloy	Ti	Al	V
Ti-6Al-4V	90	6	4

Table III

Materials Breakdown by Element Content

Material	% of ET weight	Source of	Elemental Breakdown by Element Content												
			Al	Cu	Mg	Zn	Cr	Ni	Mn	Fe	Si	C	O	H	Other
2219 Aluminum	62.21	Al, Cu	57.86	3.92	----	----	----	----	0.19	----	----	----	----	----	----
2024 "	12.86	Al, Cu, Mg	12.02	0.57	0.19	----	----	----	0.08	----	----	----	----	----	----
7075 "	9.25	Al, Zn, Mg, Cu	8.33	0.15	0.23	0.52	0.02	----	----	----	----	----	----	----	----
Other Al alloys	0.30	Al, Zn, Cu, Mg	0.27	0.01	0.01	.02	----	----	----	----	----	----	----	----	----
Stainless steels	1.74	Fe, Cr, Ni, Mn	----	----	----	----	0.31	0.17	0.07	1.17	0.02	----	----	----	----
Inconel 718	0.28	Ni, Cr, Fe, Mo, Nb	----	----	----	----	0.05	0.15	----	0.05	----	----	----	----	0.01 .015
Ti-6Al-4V	0.65	Ti, Al, V	0.04	----	----	----	----	----	----	----	----	----	----	----	0.59 0.03
Copper	0.44	Cu	----	0.44	----	----	----	----	----	----	----	----	----	----	----
Foam Insulations	5.97	C, O, N, H	----	----	----	----	----	----	----	----	----	3.58	1.19	0.15	1.04
Ablators	2.33	Si, C, O, H	----	----	----	----	----	----	----	----	0.88	0.75	0.50	0.19	
Miscellaneous	4.19	Miscellaneous	----	----	----	----	----	----	----	----	----	----	----	----	----
		Total	78.52	5.09	0.43	0.54	0.38	0.32	0.34	1.22	0.90	4.33	1.69	0.34	

plus 1.04 N, 0.59 Ti, 0.03 V, 0.015 Nb, 0.01 Mo plus traces of Zr, B, Ta.
All elements listed add up to 95.79% of the ET weight. This amount plus the 4.19% of miscellaneous materials adds up to 99.98% of the ET weight.

Table IV

Materials and Structures Opportunities Afforded by Recoverable ET's in Orbit

1. Intact Tankage - Vessels for orbital storage of cryogenic, storable and solid propellants, life support fluids, warehouse, vacuum chambers, etc.

2. Reworked or Modified Tankage - (Airlock, power, life support and thermal control systems.) General purpose workshop for manned occupancy.

3. Sectional Tankage - Individual pressure vessels, aluminum alloy stock material, insulation sheet and stock.

4. Reworked Tankage Materials

   A. Metals Recovery
   Aluminum, ingots, casting, wire, powder,
   Electrical conductors, copper and aluminum
   Silicon, magnesium, minor alloy constitutents
   Single crystal metals

   B. Non-Metallic Solids
   Urethane foam
   Silicone
   Fiberglass
   Composite materials
   Aluminum hydride propellant

   C. Non-Metallic Volatiles
   Nitrogen
   Oxygen
   Nitrogen oxides

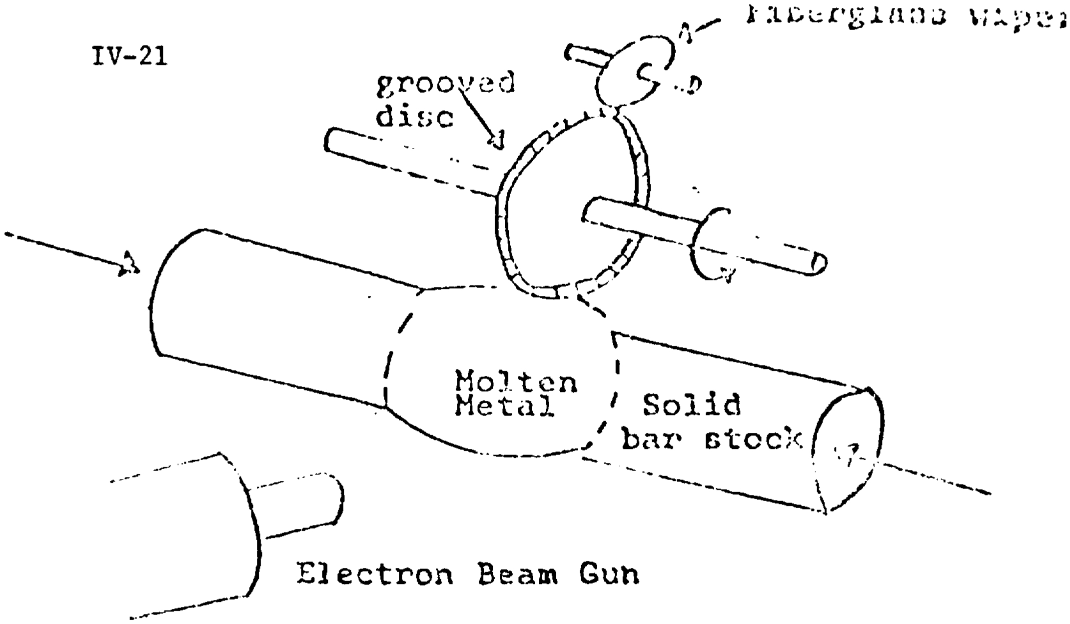
5. Compositionally Indifferent Materials - Radiation and micrometeoroid shielding, reaction mass for propulsion.

6. Metallic Structures - Large space structures, beams, castings, powder metallurgy parts, antennas, solar concentrators, thermal radiators, pressure vessels, micrometeoroid shields, manned space capsules, girders, trusses, space craft.

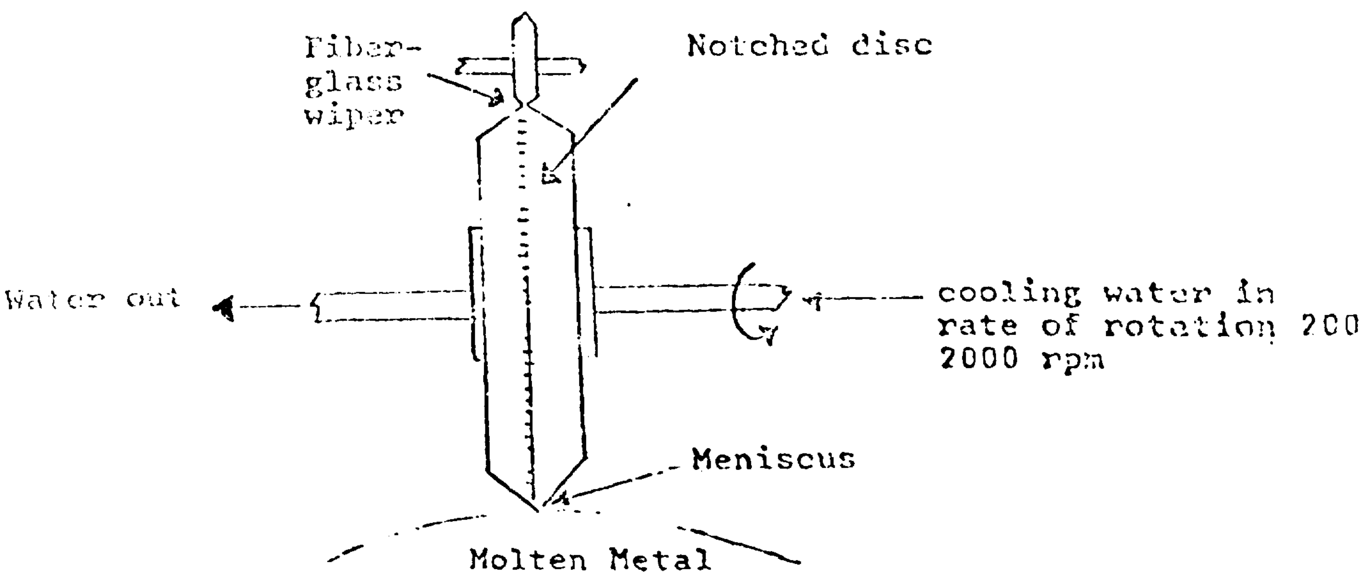
7. Non-Metallic Structures - Reentry shields, Al_2O_3, SiO_2, etc. Thermal insulation, space radiation shielding (combined with thick metal shields).

8. Composite Structures and Systems - Solar photovoltaic power systems (Amorphous silicon, thin-film systems) solar thermal furnaces, optical mirrors, refractories, space craft.

9. Non-Metallic Volatile Products - Propellants, (H_2-O_2), (AlH_3-O_2), (SiH_5O_2), (Al-O_2), (NH_3-O_2), (NH_3-H_2O_2), (N_2H_4-H_2O_2), etc.



A. Production of metal flakes by Crucible Melt Extraction (CME) Process.



B. Profile view of notched disc for producing metal flakes by CME process.

Figure 1. Battelle Crucible Melt Extraction (CME) Process for flake and wire production modified for use in zero-gravity environment.

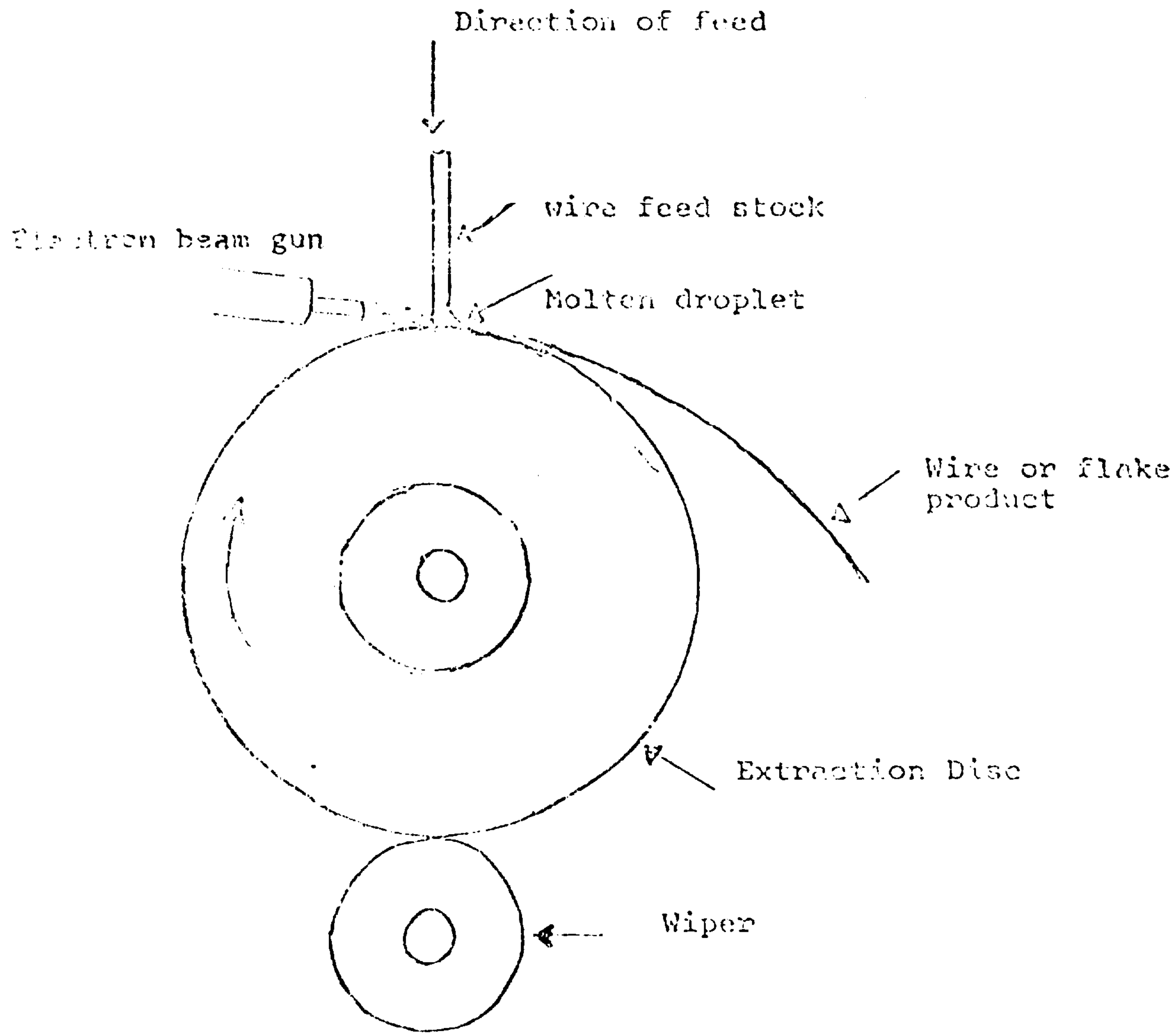


Figure 2. Schematic of Battelle Pendant Drop Melt Extraction (PDME) Process.

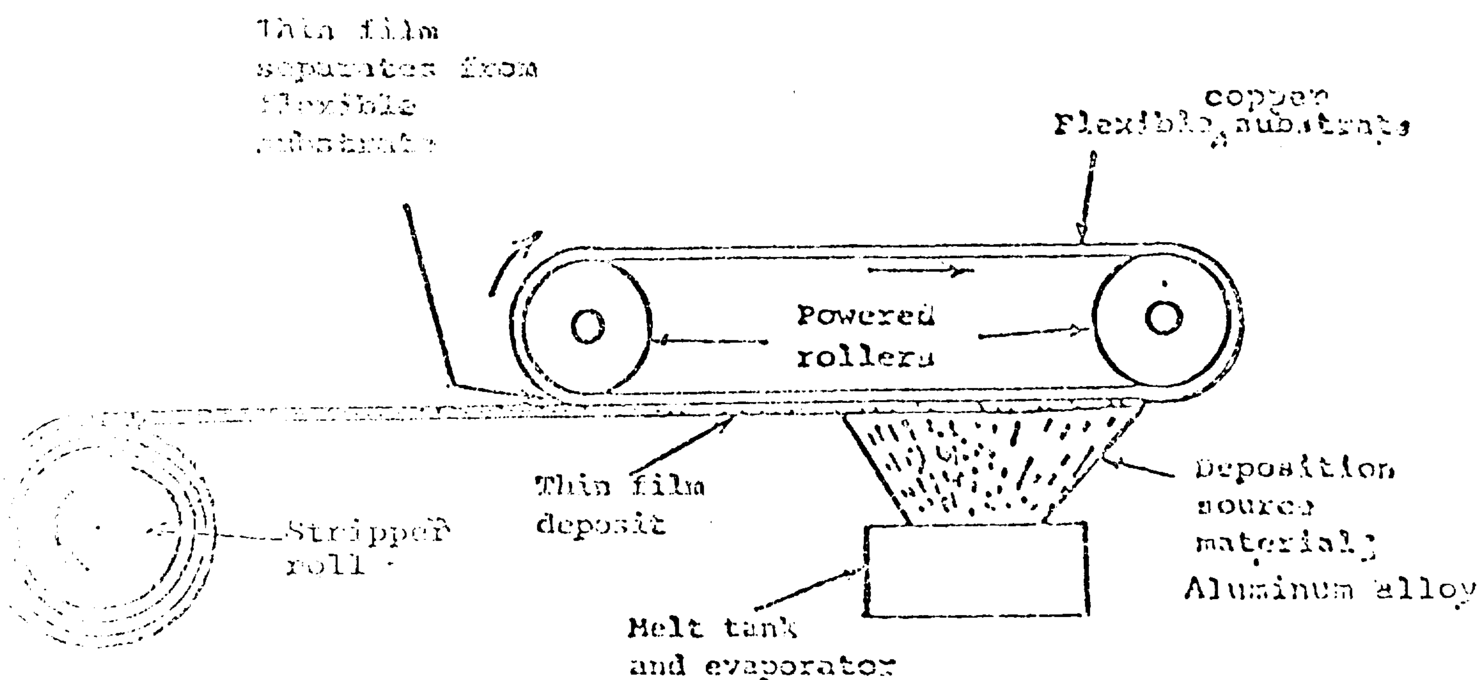
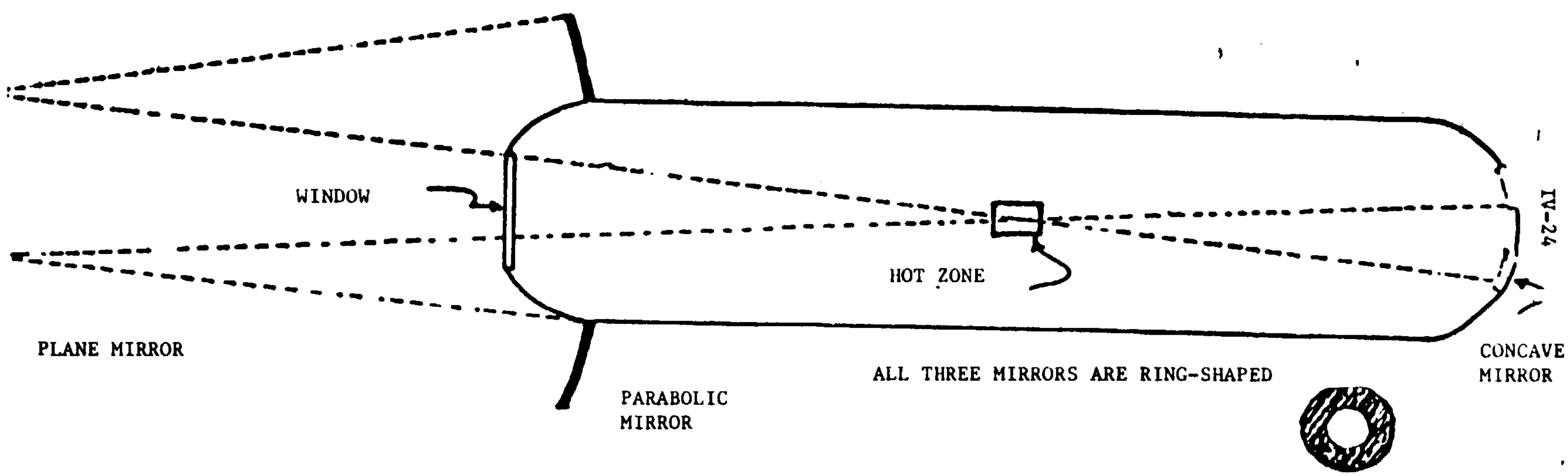


Figure 3.. Aluminum Film Deposited and Removed from Flexible Substrate

FIGURE 4

SOLAR FURNACE IN MODIFIED H_2 TANK



NOMINAL TASK - PREPARING ABOUT 50 kg Al_2O_3/hr

HOT ZONE TEMPERATURE - GREATER THAN 2300°K

THERMAL POWER AT HOT ZONE - 80 kw

COLLECTOR AREA - ~100 M^2

VOLUME OF HOT Al_2O_3 - ONE LITER

TANK WALL (770 M^2) SERVES AS WASTE HEAT RADIATOR

TANK MAY BE EVACUATED OR GAS-FILLED, AS DESIRED

V. SCIENCE AND APPLICATIONS

A. Introduction and Recommendations

In this section we discuss the basic and applied scientific experiments and operations (excluding biological and military aspects) which may be significantly enhanced through the availability in space of external tanks. Following a brief review of present uses of space, for communications and navigation, earth-oriented remote sensing, and the space sciences, we focus on the unique characteristics of orbiting external tanks. Specific experiments are then suggested which take advantage of those characteristics, and the characteristics of the tether systems, which were described in an earlier section. Recommendations are presented in Table I.

B. General Topics in Science and Applications

Communication and Navigation

One of the very first and now most prominent uses of space is in communications. Numerous military and civilian communications satellites are now in geostationary orbit, and new spacecraft are being built specically to be accommodated in the 15 foot diameter of the shuttle cargo bay. A steady decrease in the cost of long distance communication between points on earth has occurred. Continuation of this trend will require the placement of increasingly larger and more capable communication spacecraft in orbit. Larger antennas in orbit reduce the requirements of size and complexity for the numerous individual receiving and transmitting antennas and other equipment on Earth, while increasing the bandwidth.

Navigation has been improved dramatically through the creation of specialized spacecraft. The Transit system has for many years provided ships and other platforms with 200 m accuracy fixes, at a rate of several fixes per day. The NAVSTAR system is beginning to become operational, permitting continuous location in three dimensions, with accuracies of 10 m. Future development of specialized navigation systems may proceed along several lines, one of which may be moderate accuracy systems requiring minimal receiving equipment. The increased cargo width offered by certain ET cargo carrier options may lead to greatly expanded antennae in orbit, which would, in turn allow enhancement of navigational capabilities.

Remote Sensing of the Earth

During the past ten years, satellites have demonstrated the feasibility of remotely measuring many earth parameters useful for scientific studies in meteorology, oceanography, glaciology, geology, etc. Many reviews have appeared recently on the needs for, and potentials of, these space observations. We have provided a summary (without claiming completeness) of some of the instruments used and parameters measured (Table II). With the availability of a space station and/or platform, appreciable improvements in quality, coverage and time continuity become possible; in addition an entirely new suite of measurements becomes feasible from larger instruments and facilities that can only be assembled in space.

Table I

Science and Applications - Recommendations

A series of workshops should be immediately organized and held to explore specific uses of External Tanks for support of new science and applications programs in low Earth orbit.

These workshops should specifically consider the following topics and suggest other uses revealed during the meetings:

- ET's as occultors for ground and space borne observatories.

- ET as a structure to support ground installed millimeter radio reflector (7 meter diameter) for astronomy and Earth observations.

- Several ET's used to support cooperative observations such as direct-adsorption lidar or VLBI.

- ET's as shielded research volumes for experiments in gravitation, orbital dynamics of multiple small bodies, dusty zero-g plasmas, fluids research (planetary fluids terrella).

- ET's as general purpose experimental facilities which can be modified by astronaut/unmanned revisits or via telemetry from user groups (e.g., materials processing experiments, active magnetospheric experiments, ion propulsion development).

- ET's as support elements (tethers, electron sources, etc.) for active magnetospheric, plasma and terrella experiments.

- ET's as very large area (100's m^2) detectors of very high energy cosmic and gamma rays and x-rays (special windows) for long term single or multiple detector (telescope) operations.

- ET's as protective support structures for interferometers.

- Compressed ET's as components of low altitude gravity gradiometers.

- Use of cryogenic capacity (tons) and cryogenic fluids in support of experiments in LEO.

Table II

EARTH-DIRECTED REMOTE SENSING

TECHNIQUE	TERRESTRIAL	ICE	ATMOSPHERE	OCEAN
ACTIVE				
MICROWAVE				
SAR	GEOLOGICAL (FAULTS)	OPEN LEADS	---	SURFACE WAVES/ROUGHNESS
SCATTEROMETER	---	---	---	SURFACE WINDS
ALTIMETER	GEOID	ICESHEET THICKNESS	---	SURFACE WINDS, WAVE HEIGHTS, CURRENTS
LIDAR	---	---	---	AEROSOL/CLOUD PARAMETERS, DOPPLER WINDS
PASSIVE				
MICROWAVE	SOIL MOISTURE	ICE DISTRIBUTION/THICKNESS	RAIN, WATER VAPOR	SURFACE WINDS, SEA SURFACE TEMPERATURE, SALINITY
VISIBILITY/ NEAR INFRARED	VEGETATION/POLLUTION ROCK-SOIL TYPES	ICE DISTRIBUTION/THICKNESS	CLOUD DISTRIBUTION	SOLAR INSOLATION, CHLOROPHYLL, SEDIMENTS
THERMAL INFRARED	HEAT CAPACITY (SOIL CLASSIFICATION)	---	CLOUD HEIGHT, DISTRIBUTION	SEA SURFACE TEMPERATURE

Instrumentation platforms could be used for at least four different purposes in remote sensing: (i) sensor experimentation, (ii) assembly of large structures and multiple arrays, (iii) data relaying and preprocessing, and (iv) scientific observations. New sensors could be tested, evaluated and optimized. Inflight sensor calibration and intercomparisons could be performed for free-flying satellites. Large microwave antennas, and microwave and lidar facilities, could be assembled in space. Tanks are large enough to accommodate ocean scatterometry experiments utilizing both direct and nadir-looking antennae. This would allow most directional ambiguity of ocean wave motion to be removed analytically. Testing of data preprocessing schemes, processing of large data sets (images) and calculations of geographical location of in-situ platforms (drifting buoys, for example) could be performed routinely. Finally, observation platforms could continuously study regional processes (such as upwelling, for instance) to monitor seasonal phenomena (currents, winds, cloudiness), to map continental ice sheets, and also to support forthcoming large-scale climate experiments (by providing global and continuous coverage) or limited-area process-oriented experiments. Most of these applications would require global coverage and day and night data, which would mean that an optimal orbit would be sun syncrhonous with a $60-100^o$ inclination. However, a lower inclination orbit such as 25^o to 35^o would be acceptable for several climate applications which deal with tropical regions only.

Space Sciences from Near-Earth Orbit

The space sciences include scientific investigations unique to space, such as the in situ sensing of magnetospheric physical properties. On the other hand, there also exist many lines of research for which space simply offers superior advantages. The Space Telescope represents the most ambitious program of the latter category; it will extend the classical ground-based techniques of astronomy very significantly in wavelength range and sensitivity.

In over two decades of space research, many of the primary explorations in various disciplines have been carried out. External Tanks offer opportunities for innovations that will radically improve observational capability in several areas. Some wholly new lines of research will become possible for the first time. The external tanks offer an alternative lower-cost means of achieving some of the presently-planned objectives of space science.

A large millimeter/submillimeter telescope would fit intact into the diameter of an external tank. Launching such an antenna in a cargo carrier incorporated into an ET would make it unnecessary to develop the technology required to deploy and assemble a precise reflector in space.

Exciting possiblities for scientific research exist because the tanks can be formed into large, extended and stable complexes by means of tethers. Magnetospheric interactions can be studied, extended current systems can be organized to direct stimulated magnetospheric plasmas and possibly terralla type experiments can be performed in the magnetosphere. Extended arrays of tanks may be useful in astronomy (slow occultations, large coincidence arrays, interferometers) and Earth Observations.

C. The External Tank - Unique Characteristics for Basic and Applied Sciences

The physical characteristics of the external tank have been described earlier in detail, and will not be repeated here. Suffice it to say that the tank provides a large mass of raw materials, including structurally strong components. Its physical dimensions far exceed the size of any previous spacecraft, and provide an immense volume which may be moderately pressurized. This volume is protected from many external factors, and can form a Faraday cage. There is ready physical access to the volume. Hydrogen and oxygen cryogens associated with excess shuttle fuels may be employed to cool detectors, provide gaseous propellant for station-keeping, and be combined in fuel cells to produce electrical power and water. The tank could be made available to house or support large experiments for long durations of time. Finally, several tanks placed in various orbits, may be anticipated, so that arrays of measuring devices can be assembled, at distances ranging from very close to many thousands of kilometers.

With the above characteristics in mind, a number of experiments have been suggested by workshop participants, which depend on various external tank features.

D. The External Tank in Occultation Experiments

One application of an external tank left in orbit requires no modifications or special design considerations. This is to use the tank, in conjunction with a space-based telescope, as an occulting mass for the study of distant astronomical objects.

At present, the valuable method of occultation astronomy is limited to serendipitous events in which objects such as the moon or a planet pass between the earth and a bright star. Such experiments are today mostly restricted to very low declinations, and to rare opportunities. Among the accomplishments of this type of expriment are the discovery of the rings of Uranus (and possibly Neptune), separation of components of spectroscopic binary stars, measurements of the characteristics of the rings of Saturn, and studies of planetary atmospheres.

A space shuttle external tank, inserted into an appropriate orbit, would cross the field of view between the space telescope and a fairly large variety of astronomical objects. The tank's bulk, at distances up to several hundred kilimeters, would be large enough to occult distant point sources, yet far enough away to provide a sharp, sudden, light-cutting edge. It can be expected that the external tank will have a well-understood orbit, so that light curves can be related directly to the object studied.

Possible uses include discovery and quantification of planetary rings, detection of extrasolar planets, studies of binary stars, and detection of asteroidal satellites.

E. High-energy Astrophysics

The largeness of scale possible for experiments performed with the external tanks offers several interesting possibilities for astronomical observations of X-rays and γ-rays and particulate cosmic rays. The suggestions that should be pursued with more detailed studies include:

X-ray Survey

A large platform oriented by gravity gradient would be an excellent location for mounting very large-area proportional counter systems for x-ray sky surveys. For sufficient sensitivity, the total counter area would probably have to be tens of square meters. It may be possible to use an approach more akin to a laboratory experiment in high-energy physics, by involving astronauts or teleoperators (Chapter VII) for appreciable labor in orbit, rather than in the now traditional mode of large automatic space experiments.

γ-ray Occultation Experiment

A tethered pair of external tanks, or arrays of tanks, might provide an external occulter for γ-ray astronomy in a survey configuration. This survey would produce relatively good angular resolution, depending upon the spacing between the tanks.

Ion Chamber/Cherenkov Chamber

The large volume of an External Tank might be used for γ-ray or cosmic ray experiments. One possibility would be in an ion-chamber configuration; the large volume of the former hydrogen tank would permit a substantial response to brief transient γ-ray bursts expected, for example, from supernova explosions. Similarly, the tanks could be instrumented in orbit as large Cherenkov counters for cosmic-ray studies. Both fluxes and vectors might be measured with unprecedented accuracy.

F. Radio and Optical Observations of Space

Millimeter/Submillimeter Astronomy

The millimeter/submillimeter wavelengths, with the far infrared, represent a kind of "last frontier" for space astronomy. The Earth's atmosphere is virtually opaque for wavelengths in the range 0.1 - 1 mm, and the first survey (the IRAS satellite) is just at the point of launching in late 1982. A second long-wavelength survey satellite (COBE) is still many years away.

At the millimeter/submillimeter wavelengths one meets the characteristic radiation of cool objects - regions of star formation, molecular clouds in interstellar space, non-luminous bodies such as asteroids and planets, and interstellar grains or dust. The spectroscopy of such objects reveals much information about radiative, plasma, and chemical processes in regions quite remote from existing laboratory experience.

A real exploitation of space for these wavelengths will come from a capability for large-diameter optics to overcome the diffraction limit of angular resolution. Present NASA planning envisions a Large Deployable Reflector of 10-20 meter diameter to fill this gap, but the program would not reach launch until the mid 1990's under present conditions.

A slightly smaller dish of 7 meters' diameter could be launched intact within the envelope of the External Tank. Proceeding in this manner removes the need to develop costly deployment technology for precise structures, since the mirror could be finished and tested on the ground before launch. If a millimeter/submillimeter telescope could be placed in orbit in this manner, it might represent a substantial cost and time savings over present program plan.

Very Long Baseline Interferometry (VLBI)

The technique of very long baseline interferometry has brought radio measurements of astronomical sources down to angular resolutions of 0.001 arc sec. This has been achieved by intercontinental baselines involving correlated observations from radio telescopes in the U.S., Canada, Australia, and the Soviet Union among others. Even at these levels of angular resolution, there remains unresolved structure inside many interesting astronomical objects, for example, the nuclei of active galaxies where black holes may generate the tremendous energies observed in intergalactic jets.

Large radio antennae in space would extend the advantages of ground-based VLBI, by using multiple space antennae or by correlating with ground-based antennae. The advantage is not restricted to the slight improvement in angular resolution obtained from a low Earth orbit, but comes also from the completeness of the coverage of the Fourier transform space needed to create an image. Later, an extension to deep space could greatly improve the angular resolution. There is presently no NASA plan to carry out such observations, in spite of their revolutionary impact on astronomy, but the Soviet Union is actively pursuing a program of space VLBI.

Optical Interferometry

Interferometer measurements are now routine in ground-based radio astronomy. Optical interferometry is made difficult to impossible on the Earth because of atmospheric turbulence. However, given a large and reasonably stable platform in space, optical interferometry may be possible. Two modest-aperture optical telescopes could be mounted inside the protective environment of an ET. The two telescopes, if coupled by a laser system, could constitute phase coherent detectors. Even on a single ET, an angular resolution of 0.001 arc seconds could be achieved. This is sufficient to resolve structures on nearby stars and their planetary systems, or to explore small structures on the sun. The external tank would provide the infrastructure of physical protection, pointing and stationkeeping, cooling communication and data processing, all needed to conduct such delicate measurements.

G. Earth Observations

Large Microwave Antennas for Earth Remote Sensing

Microwave observation of the Earth offers a tremendous advantage over visible and infrared methods, in its ability to penetrate cloud cover. Passive microwave radiometers on spacecraft have been used to measure sea surface temperature and surface winds over the ocean, along with a variety of other parameter measurements over ice and land, and within the atmosphere. The spatial resolution achievable from the existing small (less than 1 m) reflectors is a limiting factor. For example, the 150 km sea surface temperature spatial resolution achieved by recent satellite sensors does not resolve most of the major dynamical features of ocean circulation. A single extremely large reflector, perhaps 100 m across, with a large number of off-axis feeds and radiometers in a line array, could achieve kilometer scale resolution in low Earth orbit. Smaller reflectors of about 10 m size could employ more modest line array detectors, combined with slow rotation of the entire antenna assembly, to produce 10 km scale resolution. The large size and mass of the external tank would provide the structural framework, and moments of inertia required to support such large fixed and scanning antennas.

Synthetic aperature radar (SAR) also requires large antennas, on the order of 10 m. SAR has been used for geological, oceanographic and ice remote sensing. In addition to antenna size, SAR requires substantial electrical power, and generates data rates on the order of 10^8 bits/sec. The external tank could provide the structure for antenna support, and house the necessary power supplies. Data processing on board, prior to transmission to the Earth or elsewhere, would reduce the necessary effective information bandwidth by one or more orders of magnitude.

Advanced SAR's, able to look at various angles and frequencies, will be important for measuring higher-order properties of the ocean surface wave field, and its intimate association with the overlying wind field. SAR doppler measurements of sufficient accuracy have been proposed as a means for directly mapping surface currents. In addition, SAR is an obvious instrument for military surveillance.

Lidar Investigation of Clouds and Atmospheric Properties

Lidars have the unique advantage of providing absolute range-resolved measurements in addition to providing information about atmospheric composition. These make them a powerful tool from space, particularly as a complement to visible, infrared and microwave measurements, for studying the processes governing the composition, transformation and dynamics of the atmosphere. Some of the possible applications are presented below.

Lidars can provide cloud boundary heights (and pressure) with accuracies of one meter which, in addition to other remotely sensed cloud parameters, are important in studying the radiative influence of clouds on the dynamics of the atmosphere. Time sequences of cloud height determinations can also be analyzed to infer cloudtop winds. Lidar signal depolarization measurements have been proposed to remotely observe the ice-water phase of cloud particles, and consequently to discriminate ice from water in the case of cirrus clouds, which are optically thin and from which a lidar return signal can be obtained throughout the entire depth of the cloud. Such measurements would also provide the vertical structure of the clouds and their optical thickness in the lidar wavelength (visible). Combined with a knowledge of the environmental temperature profile and simultaneous thermal radiances, these lidar measurements allow one to calculate effective cloud emissivity.

Trace species measurements and profiles in both the stratosphere and the troposphere can be expected from pulsed CO_2 lasers with heterodyne detection, and profiles of ozone, aerosols, H_2O and temperature profiles can be obtained with tunable dye lidars.

The size of such possible systems is small enough (telescope of 1 to 1.5 m diameter by 3 to 4 m long) to fit intact in the diameter of an external tank cargo carrier and therefore they could be assembled with the required precision before launch. They will require power up to 3 KW.

H. Enclosed Experiments

Gravity-gradient and Orbital Dynamics Experiments

The external tank may be used to shield out virtually all forces except gravitation from a large enclosed volume. With modest propulsion and attitude control, it should thus be possible to provide inner test masses with an ideal environment. Alternatively, at moderate altitudes two tanks may be connected by a long tether. After damping into a stable gravity gradient orientation the tether tension can be monitored to yield the gravity-gradient force (1). The gravity gradients of the Earth can be mapped to much lower altitudes by cutting and/or melting ET's into dense aluminum spheres (ballistic coefficient $\sim$ 4800 kg/m^2). Tethered pairs of spheres could be used to obtain the vertical components of local gravity-gradient force. Alternatively, perhaps three dense spheres could be placed at the vertices of a triangle made from zero-thermal-expansion beams (composites assembled in space at nominal shuttle altitude). A fourth sphere could be tethered above (i.e., radially farther from Earth) the three triangularly positioned spheres forming a tetrahedron. Compression and tension sensors on the six connective members could yield the full vector of the local gravity gradient. Detailed analyses will be required to determine the spatial and Eotvos sensitivity of such a tetrahedral system.

Detailed knowledge of the Earth's gravity field at fine spatial resolution is required for studies in geodynamics and ocean dynamics (since ocean currents produce small but detectable deviations of the ocean surface from the marine geoid). Likewise, gravity gradient information is useful to geophysical and commercial exploration of the crust of the Earth. Full knowledge of the gravitational field is relevant to high precision knowledge of orbital and ballistic (ICBMs) trajectories. Suggestions for obtaining this information by measuring the vertical gradient of the Earth's gravity field are based on having available substantial masses in orbit (2).

Effects of very low velocity collisions (energy conservative and dissipative) may be studied by releasing test particles with appropriate physical properties inside the hydrogen section of an ET (3). The ET could be gravity-gradient stabilized or equipped with drag-compensating thrusters. Motions of the various test masses could be optically monitored. These experiments would be relevant to negative diffusion phenomena which have been suggested to explain the fine structure of the rings of Saturn and to the mechanics of debris clusters in space.

Gravity Related Experiments

The inner volume, protected as it is from all nongravitational forces, would also provide conditions for general relativity experiments. Strain gauges connected to internal masses give precise measurements of nongravitational forces on the tank. The tank interiors provide adequate volume within which to measure gravitational gradients. Such measurements would provide truly sensitive tests of the details of classical gravitational theory. Such phenomena as graviational radiation or the dynamical effects of the Earth's rotation (the Lenz-Thirring effect) could be examined.

Other Enclosed Experiments

ET's should offer unique opportunities to conduct long-term experiments on fluid systems. Hart (4) has proposed to simulate a planetary or stellar atmosphere in a zero-gravity laboratory by placing dielectric fluids about a central sphere which is electrically charged. The gradient electric force on the dielectric fluid can simulate gravitational attraction of a central body. It appears possible in principle to dynamically model the atmospheres of the Earth and thereby open an experimental avenue to climate and weather research which could complement the computational approaches being pursued by NOAA, NASA and other institutions.

ET's should be attractive experimental volumes within which to study dusty plasmas. Dusty plasmas are encountered in interstellar dust clouds, on bare surfaces such as the moon or particles in planetary rings and may be relevant to containment of plasmas in controlled thermonuclear fusion due to ablation of wall surfaces.

I. External Experiments

Exo-atmosphere flow dynamics

The outer limits of the upper atmosphere, in the region between 150 and 400 km, includes the area where the mean free path for molecules becomes comparable with the scale of various man-made orbiting objects. The flow dynamics and effective drag coefficients about such objects is an interesting and important area of research. Specific experiments need to be conducted to better understand and predict the response of large orbiting spacecraft in very low Earth orbit.

Plasma Experiments

Tether-specific Experiments

The extremely long tethers (10's of kilometers) which have been proposed in an earlier section offer a number of research opportunities. If the tether is a conductor, antennae for extremely low frequency radio experiments and communication may be assembled (5).

The emf generated by long conductors in orbit, cutting through the Earth's magnetic field lines, can be substantial, and sensitive magnetospheric experiments can be carried out. For example, measurements of the perturbing effects of a long tether could shed light on the production of decameter radiation and answer fundamental questions on the interactions of large structures with the space environment. From a large mass in low Earth orbit, long tethers can be lowered to probe the region down to altitudes of 120 km or perhaps lower, so as to chemically and mechanically probe the properties of that part of the atmosphere which is otherwise inaccessible. Shuttle supported versions of this experiment are under consideration as a joint United States-Italian project.

Other Possibilities

Single tanks offer opportunities for experiments on interactions of large structures ($\gtrsim$ 10's m) with magnetospheric plasmas. The residual propellants or special gases contained in cannisters inside the intertank region could be vented and the local effects observed. Robots could be used to place conductive sheets over various portions of the electrically insulative surface of the tank. Then current flows to and from these surfaces could be observed. Photoemissive layers could be deposited in prearranged (even changeable) patterns to provide current sources. Holes could be cut in the ET walls to provide sinks for the local plasma.

The possibilities for creating temporary miniature magnetospheres should be considered. An ET could be equipped with a fuel cell power system and electric coils. A strong magnetic field could be created about the tank (or a section thereof). The interactions with local plasmas could be studied with free flyers moving about the tank.

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VI. MILITARY APPLICATIONS

A. Introduction
B. Reconstitution of Assets
C. Concealment of Payloads
D. Payloads
E. Extended Payload Capability

A. Introduction

The purpose of this section is to briefly highlight some characteristics of STS external tanks which might provide potential benefits for DOD missions. The remainder of the section constitutes the basis for these highlights. No attempt has been made to duplicate the depth of analysis found elsewhere.

B. Reconstitution of Assets

In a conflict which results in the destruction or degradation of our space capabilities in communication and observation, a method of repairing or replacing these assets within a short time may be critical. External tanks in orbit could be useful as containers, as large masses for orbital maneuvering, or as a source of materials.

As a container, the external tank could be used to store satellites, parts of satellites for repairs and servicing, and propellants. Storage of complete satellites is probably the nearest term possibility, deployment could certainly be activated remotely as illustrated in Figure 1. Storage in the external tanks provides protection from micrometeorites, electro-magnetic pulses, particulate showers and radiation, of both the natural and man-made variety.

In order to be useful for varied missions, the storage capability should be distributed in various orbits. In addition to rapid replacement of assets in their appropriate orbits, such proliferation improves survivability, especially if decoys are also deployed. A small number of linked tanks should be used for each storage facility. A control package for reboost, deployment, and intermittent attitude control would be required for each facility.

Storage of satellite parts, subsystems, and propellant must be coupled with teleoperation, robotic capabilities or man-tending for repairs, servicing and refueling. A man-tended depot concept is illustrated in Figure 2. This concept assumes that the shuttle or some manned vehicle will rendezvous and attach while operations are performed in EVA. The work area provides a controlled environment with respect to contamination, illumination, and heat loads, and a bracing structure for servicing operations. An asset-retrieval vehicle such as the Teleoperator Maneuvering System (TMS) would be required. Incorporation of a habitat module is also possible. So far panels, booms and other extensions on some satellites may require restow so that they will fit inside the depot.

Use of the tank as a large mass for orbital manuevering (as a tethered counterweight) is described thoroughly in a later section.

The materials of the external tank may be reprocessed. Of particular use to the DOD would be aluminum pellets produced as described in the "materials" section of the report. A cloud of these pellets could be directed to re-enter the atmosphere over an area of interest. The burning particles would illuminate a considerable region. The same cloud could be used as a short-term, emergency reflecting surface for communication or data transmission, or as chaff to fool radar or conceal assets. Finally, the cloud might be useful as an offensive or defensive weapon. Many of these functions could be performed separately or in combination.

C. Concealment of Payloads

The External Tank offers an unparalleled opportunity for the concealment and hardening protection of sensitive payloads. The aluminum structure is opaque to any sensor and would present a constant radar cross-section regardless of contents. In addition, the metal skin combined with the already present thermal insulation will serve to reduce the effectiveness of radiation-type weapons.

The tanks could be employed in two ways: passive and active. The passive mode would consist of satellite storage as discussed above. Military payloads could be safely warehoused inside the structure, safe from prying sensors until needed. For security reasons, communication with the warehouse would be minimal. Interrogation could be performed at certain times by tight-beam laser from another space facility.

In the active mode, the tank could actually become more of a space "fort." Here, the payloads would be operational inside the ET. If solar powered, the panels could be normally deployed and be retracted in an overtly hostile environment. A nuclear power system could reduce observables and eliminate power store in LEO. Radiators could be retractable or body mounted. Sensors could also retract as in Figure 3, have periscopes, and be redundant.

Another advantage of the fort concept is the availability of several types of sensors to share utilities such as power supplies and reaction control systems. These systems should, of course, also be made as redundant as possible within the realm of practicality. Separately stabilized sensors could save attitude control propellants by reduing the stabilization requirements for the ET.

Fort concealment would be further aided by the use of empty tanks as decoys. It would not be difficult to dress up a large number of surplus tanks that were being stored for later use with the proper holes and appendages, forcing enemy planners to expand copious resources to ensure a kill.

ET's would have two additional uses in concealment. When material salvage and processing becomes routine, individual satellites could be hardened with the aluminum extracted from ET's as shown in Figure 3. This could be done either by depositing the metal on vulnerable areas of present assets or actually fabricating the vehicles in orbit out of the available ET materials and using electronics transported from the manufacturer on the earth.

Equipping ET's for either active or passive use would probably be a combination of pre-launch preparation and on-orbit implementation. The attachment pads, fittings, light-weight electronics, attitude control hardware and propellant lines and similar low volume, low mass components would be installed pre-launch with minimum impact on the ET's primary function. The additional work would be carried out on-orbit, initially out of the orbiter and eventually out of a LEO station.

D. Payloads to Deep Space

Use of the ET as the core of a deep space delivery vehicle (very large geosynchrous facilities, translunar space station, etc.) is usually postulated upon fueling up the ET together with its payload in LEO and using (say) an SSME attached to this vehicle to launch to the ultimate destination.

The problem with this scenario is in delivering the large quantity of cryogenic propellants to the ET. This must occur fairly rapidly to minimize boil-off losses. The logistics will be demanding in terms of many dedicated shuttle launching over a limited time and will therefore, represent a high cost penalty and a possibly unacceptable impact on shuttle availability for other purposes.

Logistics can be improved by eliminating dedicated shuttle flights for carrying cryogenic propellants. This alternative would work as follows:

The dedicated ET would be launched conventionally as a shuttle propellant tank, but equipped with the necessary payload interfacing and a low-thrust engine.

Once on orbit at LEO, an initial propellant loading would probably be added to the residuals left from the launch. This initial loading would otherwise be volume limited (the current average achieved mass load factor of the shuttle mission model is .4).

Once the initial charge of propellants and the payload are on board the deep space ET based vehicle (ETBV), the unavoidable heat leakage will begin to boil off cryopropellants. These would normally have to be vented. If they are burned in additional low thrust engine, the ETBV will begin to spiral out to a higher orbit.

The rate will be a function of the rate of boil-off and can be tailored by proper heat transfer control to produce the optimum mixture ratio of oxygen to hydrogen. Thus, the otherwise wasted cryopropellants can be used to add to the energy state of the ETBV and attached paylaod.

As the ETBV slowly spirals out (a process requiring months, if the heat leak is sufficiently low), subsequent tanking flights will be performed by OTV with automated docking to the ETBV for propellant transfer. This has already been demonstrated by the Soviet Progress tanker-cargo vehicles which perform these functions for Salyut.

An OTV will be able to deliver a higher fraction of its propellants at first, and less as the ETBV moves to higher and higher orbit. However, in this way the insulation properties required on the ET are not excessive (and may not even exceed what is already provided) and the energy otherwise lost to boil-off is gainfully employed.

The goal is to have the ETBV arrive at its launch-to- ultimate destination orbit fully fueled and carrying its payload. A final checkout and it would be ready for launch.

Studies are necessary before feasibility of this scenario can be evaluated. The trade-off between insulation mass and a refrigeration system needs to be evaluated. It would seem that trade will favor insulation, particularly if boil-off is not wasted, but this needs to be quantified.

The trade-off between OTV delivery flight frequency, rate-or-spiral-out of the ETBV and the mass fraction (including payload) of the ETBV must also be evaluated. In short, a sensitivity analysis of these variables may reveal that LEO loading is better.

E. Extended Payload Capability

A primary benefit of taking the external tank into orbit is that it allows further optimization of the STS for greater payload weight capacity. Orbital storage and subsequent use of excess propellants from the external tank and the orbiter OMS tanks for use in upper stages is an example. As another example, shuttles with excess capacity can carry experiments for on-orbit storage in ET's until later use. DOD missions could, of course, benefit from nearly all of the advances discussed in this report.

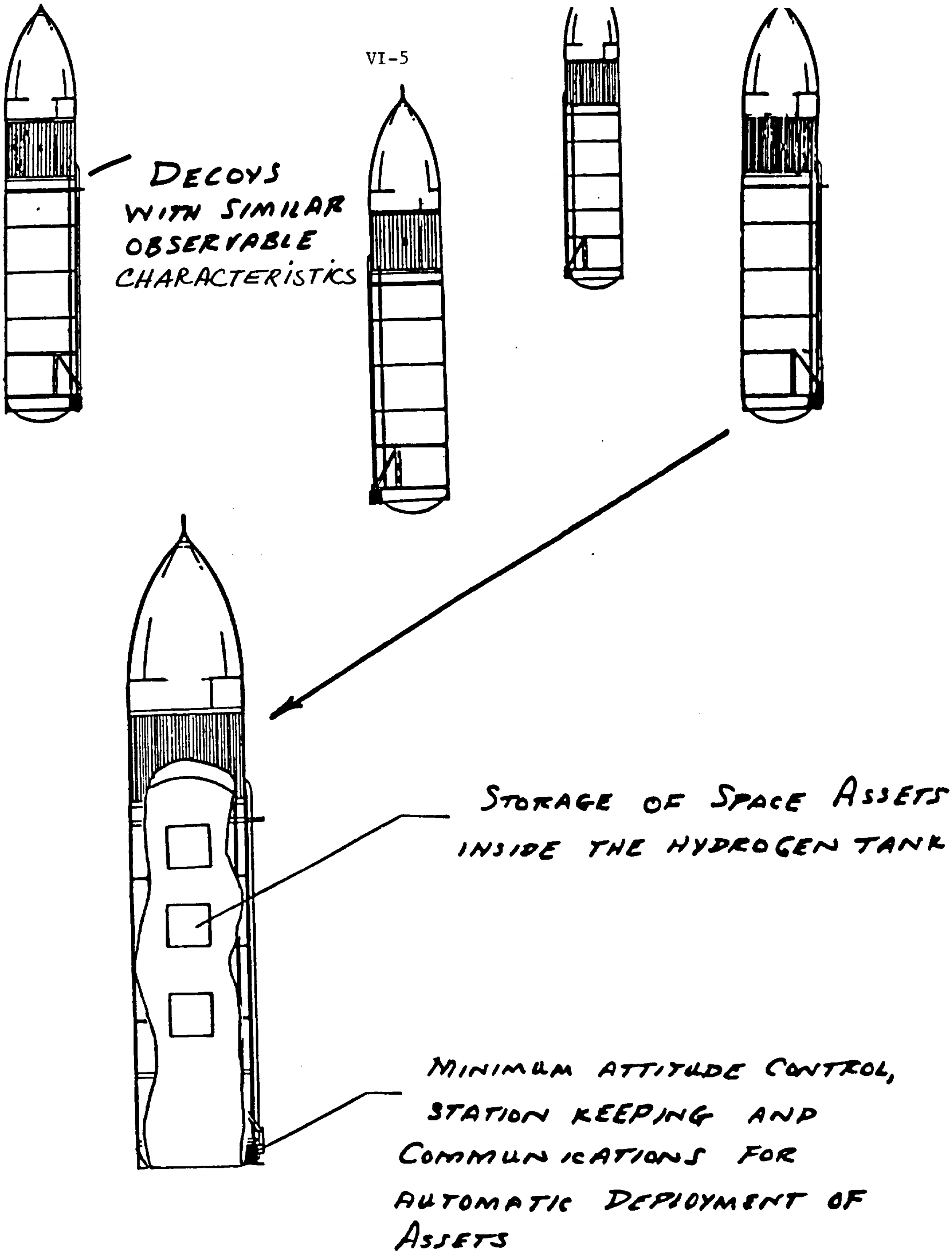

FIGURE 1. STORAGE CONCEPT FOR SPACE ASSETS IN THE ET

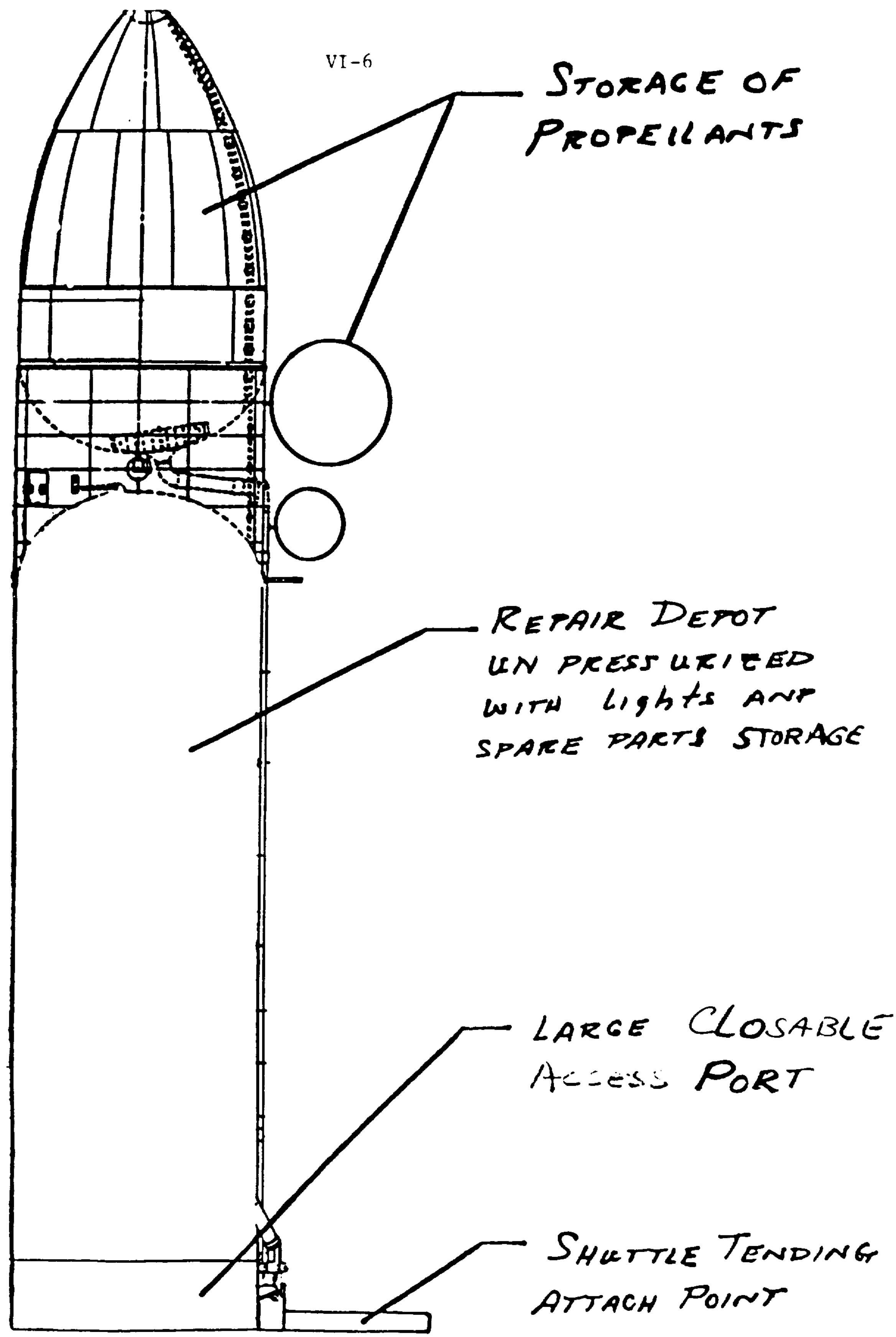

FIGURE 2. ET BASED REPAIR DEPOT

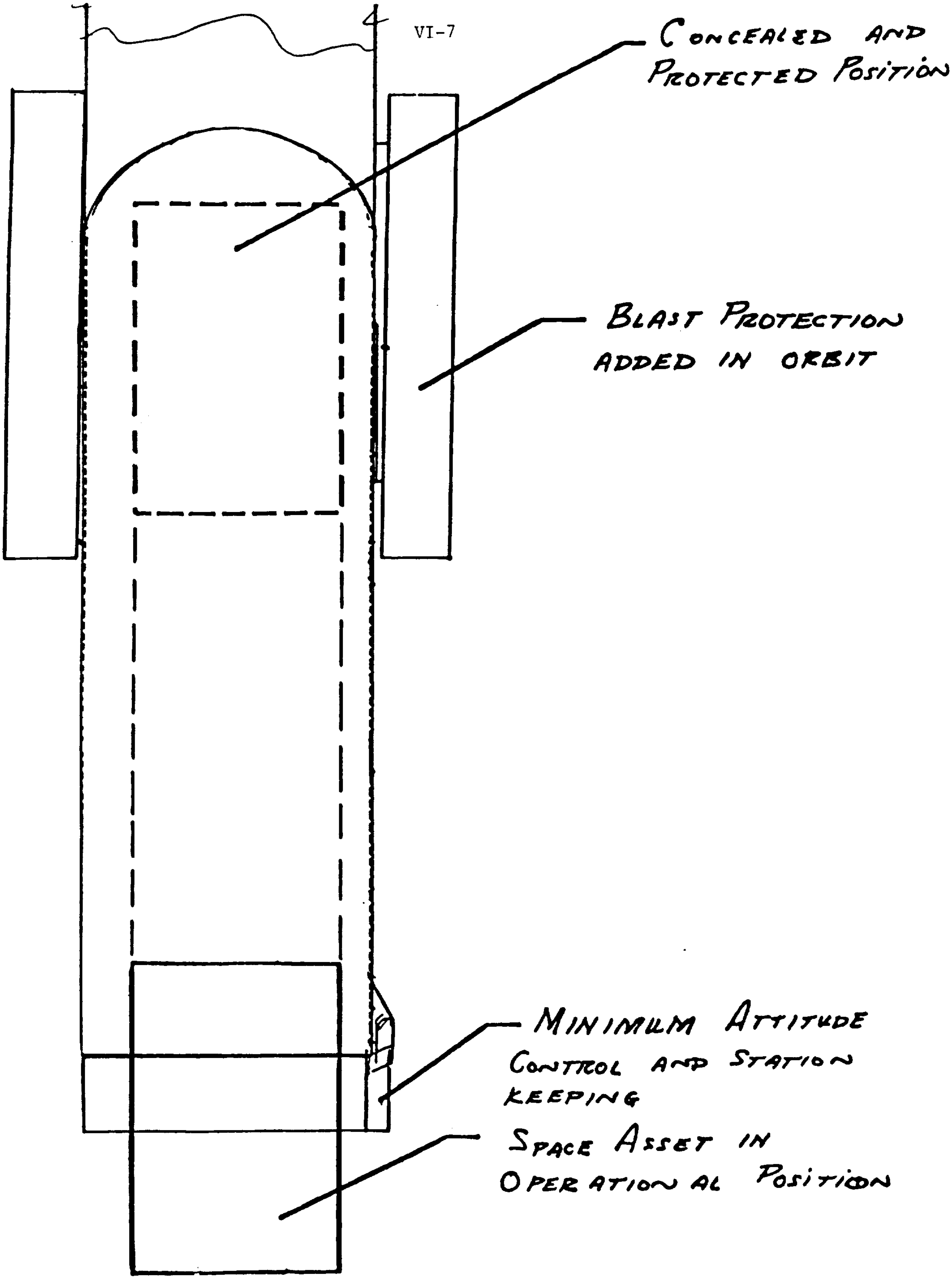

FIGURE 3. PROTECTIVE PAYLOAD VEHICLE

VII. LEVERAGING HUMAN EFFECTIVENESS IN SPACE

A. Introduction and Recommendations

Utilization of External Tanks (ET's) in low Earth orbit (LEO) and beyond is relevant to the strong interest of many engineers and scientists in establishing more flexible, continuous and supportive access by humans to operations in space. In particular, the ET can be used to test and develop remote control systems to "leverage" human effectiveness in space.

Mechanical "hands", general purpose tools and facilities which can be monitored/operated/modified remotely from Earth or by people in safe enclosures in space are desired, possible and can provide the "leveraging". New types of experiments and engineering demonstrations in space could be conducted by such techniques. Safety and effectiveness of astronauts could be enhanced by providing continuous remote support. Faster development times might be possible when man-rating takes up a smaller portion of a given activity both on the ground and in space.

Table I gives two general recommendations of this group. We emphasize that a broad range of inputs from groups outside NASA should be actively sought. The boundary of cost-effective operations in space versus supplying support only from the ground could change continuously and rapidly for the foreseeable future. This will be due to the rapid advances in computers, robotics and manufacturing technologies, the accumulation of experience operating advanced facilities in space, the creation of more comprehensive facilities in space and the almost certain larger numbers of people on Earth who would become directly involved with tasks off Earth by means of telemetry. Table II highlights the unique opportunities ET's repeatedly offer for learning-how-to and actually leveraging human effectiveness in space.

Two seemingly extreme approaches have characterized our entry into space. Unmanned spacecraft precede people into previously unpenetrated regions of space. Limited remote control has been possible by means of telemetry. Manned flights to LEO and to the moon on the other hand, have conveyed massive equipment from Earth, and generally, only the astronauts had direct physical control over equipment operations in space. There has been in spite of this dichotomy, sharing of technologies and operating procedures by the manned and unmanned programs.

The early unmanned Surveyors (lunar landers) and Mars Vikings had television cameras and small scoops which were operated remotely from Earth. Many television cameras used on the moon during the Apollo program and on the Space Shuttle could be operated remotely from Earth. The USSR operated two unmanned rovers on the moon; the U.S. deployed three small cars driven by astronauts. Unmanned "Progress" ships have automatically docked with a Soviet space station to provide new supplies. Astronauts onboard the Space Shuttle operate a large mechanical arm to deploy satellites from the cargo bay of the Shuttle.

Other possible uses of remote manipulation have been proposed and in some cases pursued to the ground demonstration phase. Comsat and the

TABLE I

Specific Recommendations

NASA and DOD should conduct studies of the uses of telepresence, robotics and advanced manufacturing in low Earth orbit using external tanks. Consideration should be given to:

- involving a full range of technical experts and possible users.
- ground-based demonstrations.
- in-space demonstrations/utilizations.
- implications of continuous telepresence, robotics and advanced manufacturing capabilities in space.
- implications for space station(s) requirements, design and operations.

The overall program should emphasize immediate goals in a flexible way. Great emphasis should be placed on "learning while doing."

TABLE II

HUMAN LEVERAGING

ETs OFFER:

- OBJECTS AND TASKS FOR PRESENT ROBOTICS AND ADVANCED MANUFACTURING TECHNOLOGIES (AMT)
- RESOURCES FOR LEARNING AND EVOLVING IN THE 1980's A GROWING SPACE MANUFACTURING CAPABILITIES

POSSIBLE APPLICATIONS IN SPACE:

- ASSEMBLY OF ETs
- ATTACHMENT OF HARDWARE (TETHERS)
- REPLACING AND/OR AUGMENTING ASTRONAUTS IN DANGEROUS TASKS
- PROVIDING STRUCTURES WITH/WITHIN/ON WHICH TO REMOTELY CONDUCT EXPERIMENTS, ENGINEERING DEMONSTRATIONS, DEVELOP FACILITIES
- REVISIT TO EVOLVE CAPABILITIES
- MULTIPLE FACILITIES (AS NEEDED OR DEDICATED) ACCESSIBLE BY DIVERSE GROUPS

NASA/Marshall Space Flight Center have demonstrated a remotely controlled spacecraft which could rendezvous with a communication satellite and refuel the comsat and install new units (1). Engineers at the Goddard Space Flight Center have proposed advanced, remotely operated flexible assembling centers which could be deployed in a volume similar to the cargo bay of the Shuttle (2). Such systems are potentially capable of completely disassembling and assembling complex spacecraft. Great scientific justification is seen for remotely controlled rovers to explore the moon and asteroids (3). It has been argued (4) that a wide range of exotic materials processing experiments could be rapidly conducted onboard an unmanned satellite (the unmanned experiments satellite could be revisited periodically by the space shuttle).

Future tasks, such as assembly of large structures in space will require robotic assistance (5). Additional manufacturing functions of mining, processing to obtain engineering materials, manufacturing and testing have been examined under NASA contracts related to space solar power stations (6,7) and in summer studies (8,9). Deployment of remotely operated "hands" and tools in space is intimately intertwined with developments in computer science and specifically the emerging field of artificial or machine intelligence. A year-long study funded by NASA-Office of Aeronautics and Space Technology found that machine intelligence and robotics would have profound effects on all aspects of NASA ground and space operations (manned and unmanned) and should receive considerable research support (10, 11).

The opportunity for NASA to establish remote manipulative access to space occurs at a uniquely opportune time. Much of the broad range of relevant human skills, machines and software that will be needed are being developed already to meet terrestrial needs. Our modern industrial society requires the technologies of robotics, advanced computers and machine intelligence. Coverage of these fundamentally new and rapidly burgeoning technologies extends from the popular press (12) to virtually all arenas of the technical literature.

Human work is changing rapidly in the advanced countries (13). People are leaving the physical volumes in which farming, mining, manufacturing and distribution occur. Flexible machines are occupying more of the total physical volumes of production. Less than 15% of the U.S. population is directly involved in farming, mining and manufacturing segments of the economy. The "hands-on" fraction is even smaller. The fraction will continue to decrease as more flexible hierarchies of machines and computers are introduced. Computers are rapidly entering the activities of design and administration. Communication cables and radio systems increasingly link people at remote computer terminals to the production volumes.

It is possible that the communication links between terrestrial designers/administrators and the terrestrial production volumes can be effectively adapted and extended to facilities in Earth orbit. Initially small production volumes can be placed in near-Earth space. Directions can come from people on Earth or in space.

External Tanks placed in controlled orbits about the Earth can be the first major containers for production volumes and the primary sources of working materials. They can provide the means by which we learn to develop growing manufacturing capability off-Earth in the immediate future and do so economically. The ET's can be an inexpensive, readily available resource base (350-1100 tons/yr) for use in Earth orbit rather than being wasted.

B. Burgeoning Technical Opportunities

Six participants of these two workshops on utilization of the External Tanks (8-9 March 1982* and 23-27 August 1982†) have extensive contacts with the commercial/laboratory developments in advanced manufacturing and robotics and the applications of these technologies to space operations (14). In view of the rapidly advancing state of the arts in these fields it is appropriate to provide snap shots of these arts and the implications for space applications.

The state of the art of advanced manufacturing and robotics allows the rapid employment of flexible, manipulative and productive systems on the external tanks in space.

It should be possible to provide many technically sophisticated groups (national laboratories, industrial groups, universities) direct access to space with minimal administrative, procedural and financial interactions with present space organizations using remotely aided facilities in external tanks. New independent groups can begin to function in space.

Manned spaceflight can be made safer and more effective by:

- Providing tools controlled from Earth for operations outside the manned spacecraft.
- Providing astronauts an electronic means to operate outside their spacecraft without and/or in coordination with extra vehicular activities (EVA). Effective astronaut work time (more hours of productive effort) in space would be extended.

A wide range of activities in space (e.g., docking and attaching tethers or tanks) supportive of manned activities can be freed of the need for man-rating specific operations and/or equipment.

Robotics and advanced manufacturing could allow effective manipulative access to space vehicles and external tank resources under hazardous conditions (hostile situations or natural events such as solar storms).

With reasonable development programs it should be possible to rework ET and supplemental materials in space, to provide products and services without the penalties of launch from Earth. The utility of shuttle cargo capacity would be increased. New classes of experiments in space and flexible experimental facilities not dedicated to a particular objective would become possible.

Procedures developed in LEO can be extended readily to geosynchronous orbit, the moon and later to asteroids and other solar system bodies.

There should be a strong synergistic interaction between terrestrial and in-space robotics on the one hand, and advanced manufacturing on the other, as both communities respond to rather different physical and economic conditions. References 15 through 21 describe some of the recent developments.

C. An Example of a Possible Application

In the following section we explore the characteristics of a state-of-the-art robot which could perform extensive manipulations of one or more external tanks. We refer the reader to the other sections of this report for other possible uses of the external tanks which can be significantly expedited by the use of robotics and advanced manufacturing facilities in space.

Challenging tasks and experiments which can be carried out with the Shuttle External Tank (ET) in space include:

1. Maneuvering the tank;
2. Attaching two or more tanks together after docking;
3. Attaching devices to the tank or removing others from it via fixtures;
4. Cutting, drilling, machining, welding or other machine shop operations on the tank structure itself;
5. Mechanical or chemcial manufacturing operations using tank inherent materials.

Each of these operations will require the application of intelligence in the form of on-site humans or remotely directed teleoperators, remote arms or robotic devices.

Because the on-site presence of humans will require a costly man-rating, it is believed that the use of robotics for such operations will prove to be most cost effective, especially since no robotic operations beyond present state-of-the-art capabilities (ref. 15-21) are foreseen.

The state-of-the-art makes it now possible to program a robot with multiple limbs, manipulators, etc., to carry out any sequence of motions which can be defined (15-18). The ET as an object is perfectly defined. Therefore the sequence of motions required to move the robot anywhere on the surface of the tank can be readily defined.

Likewise motions required for the robot to position, i.e., point, a small rocket motor for maneuvering, such as docking, can also be readily defined. The required pointing direction could be supplied from an external stable inertial reference system. Similarly the robot motions required to install fixtures, mate parts, add bolts, etc., can be readily defined.

The envisioned robot should have the following characteristics to carry out the foregoing mission. It will have the general requirements as follows:

1. The ability to "walk" (or fly) about the surface of the ET.;

2. Umbilicial connections to a cargo section should be provided for power and computer;

3. Instructions from a large capacity system (main frame equivalent);

4. It should be able to change tools and arm fixtures;

5. Four legs will probably be required for stability in walking;

6. It will probably need three arms where two would used for grasping and holding, and the third for tool operations.

7. A vision system.

The robot would keep an accurate record through the computer of its position and orientation relative to the ET. Through reference with the inertial system and docking radar it could accurately point a rocket motor for maneuvering of the ET without vision. Vision is needed for operators or for fine tuning of position in manufacturing operations. (Binocular television will probably be needed for artificial vision support via the local computers. Monocular may be sufficient for remote monitoring by human directors.

Maneuvering and docking of ET's by the robot should be possible. It should carry a small rocket motor for maneuvering and docking the ET. A set of small maneuvering jets would allow the robot to fly and maneuver while in flight. It must be noted that incorporation of a "flight ability" in the robot would require that the ET be equipped with an independent registering method for the robot to establish its position accurately on the tank upon "landing". These could be small magnetic coded markers installed under the insulation which the robot could "read".

Positioning and pointing accuracy sufficient to make required manufacturing operations and to "point" the rocket motor for maneuvering and docking the ET (Note: position reference would come from stable platform in a cargo section of the ET).

The robot should carry a tool change pack similar to an automated machine tool with an available tool selection kit including: drills (various size bits), cutter (saw or laser or scissors), grasper, wrench, bolts, and a welder.

We note that power for the early operations could be provided by operating fuel cells off the residual oxygen and hydrogen in the external tank(s).

It is proposed to use shuttle attachment points for fastening two ET's together. One would build a fixture which is effectively a double-ended shuttle side of an ET attachment fixture. The robot in space can attach this fixutre to three points of one tank and complete the fastening as necessary. It would also be possible to sacrifice a third tank for building attachment mechanisms in space to attach two or more ET's together.

Following linking operations or interspersed within them at idle periods the robot would be available to carry out manipulative operations involved with space manufacture, science, biology, or other important ET based experiments.

In addition to the robot as described other support facilities would be needed in space on the External Tank. Maneuvering and docking radar and/or TDRSS (tracking and data relay satellite system) could be used for obtaining relative position and velocity vectors between tanks for docking. Possible use of horizon or star sensors could aid in position determinations. An inertial reference system or the TDRSS could be used for establishing and maintaining a reference for the robot-tank system. Horizon and star sensors and other devices may also be helpful here or may serve in lieu of the above. Fairly extensive computing facilities (equivalent to a main frame) would be necessary. A solar cell or fuel cell power source would be needed. Communications for human operators and for coordination of work between two robots on adjacent ET's must be provided.

There are research and development needs. A "firm" method of attachment of the robot to the surface of the ET as it walks about is required. Attachment options include a hook system for grasping the surface insulation or drilled holes and bolts might attach a robot "foot" to the surface of the tank (Note: this method destroys the pressure integrity of the ET). A "rail" system on the surface of the ET could provide a continuous prepared "foot hold" for the robot. A proposed rail system is shown in figures 1 and 2 (suggested by T. Taylor).

One possible track system (illustrative; fig. 1 and 2) consists of a long thin plate with a series of holes. The robotics equipment is designed to walk along the rail using the holes for support. The straight rail is held at each end or at intervals along its length by preinstalled anchor devices under the TPS insulation at the interior ring frames. The curved ring frame rails also use the same anchors and provide 58 directional change locations. Some areas of the tank surface are complicated by the propellant lines and cable trays of the ET.

The track might be installed in orbit. It could be designed to evolve as the robotic equipment is refined. Initial robots will use tether umbilicals. Later robots might take their power and communications from the track itself through wires near the rails.

Engineering design and development of the required robotic system is necessary. We note that individual required operations have all been carried out in previous robotic studies for terrestrial applications. Inclusion of all these capabilities in one robot has not yet been carried out; however, this is simply because they have not been needed on Earth. No major difficulties are forseen (15).

It should be noted that, except for the robot itself, flight-rated parts such as inertial reference systems, TDRSS components, horizon and star sensors, a rocket motor for maneuvering the ET via the robot, and reaction jets for flight and maneuvering of the robot itself, exist or can be developed with minimal R&D.

D. Other Examples and Comments

There is a wide range of possible first applications of robotics to ET missions. They need not all be of the larger scale necessary to mate two ET's. Small, low force-level robot arms are available which operate under microcomputer control. These would be useful in manipulating small cannisters of biological experiments. For example, cannisters inside a slowly rotating ET could be shifted to different radii from the spin axis thereby changing the apparent gravity; alternatively, biology containers could be placed behind various masses to provide exposure to different types and levels of natural radiation. Robot arms could be used in agricultural experiments to plant seeds, extract plants, irrigate plants and transfer plants to analytic devices (private communication, D. MacElroy, NASA/Ames).

Similar simple applications exist in scientific and materials projects conducted on board ET's. Early applications might involve shifting filters, apertures, or detectors. Liquids, ferrofluids or powders could be manipulated. Gases and liquids could be released from the main propellant tanks or other reservoirs. Low force level robots could be used in powder metallurgy/binder systems to make new low stress parts.

Thought should be given to simple robot/monitoring systems and kits of components which could be sent up on various flights. University students could contribute to defining the "kits" for various purposes and then experimenting with the kits in orbit. Possibly American and foreign universities could form cooperative programs. Some funding could come from foreign governments.

It is difficult to imagine even a fraction of the new capabilities modern computers/robotics systems controlled from Earth could evolve in space if operated creatively (even competitively) on many different ET's. Considerable effort should be stimulated by NASA to explore and develop the possibilities.

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ET SURFACE TRACK

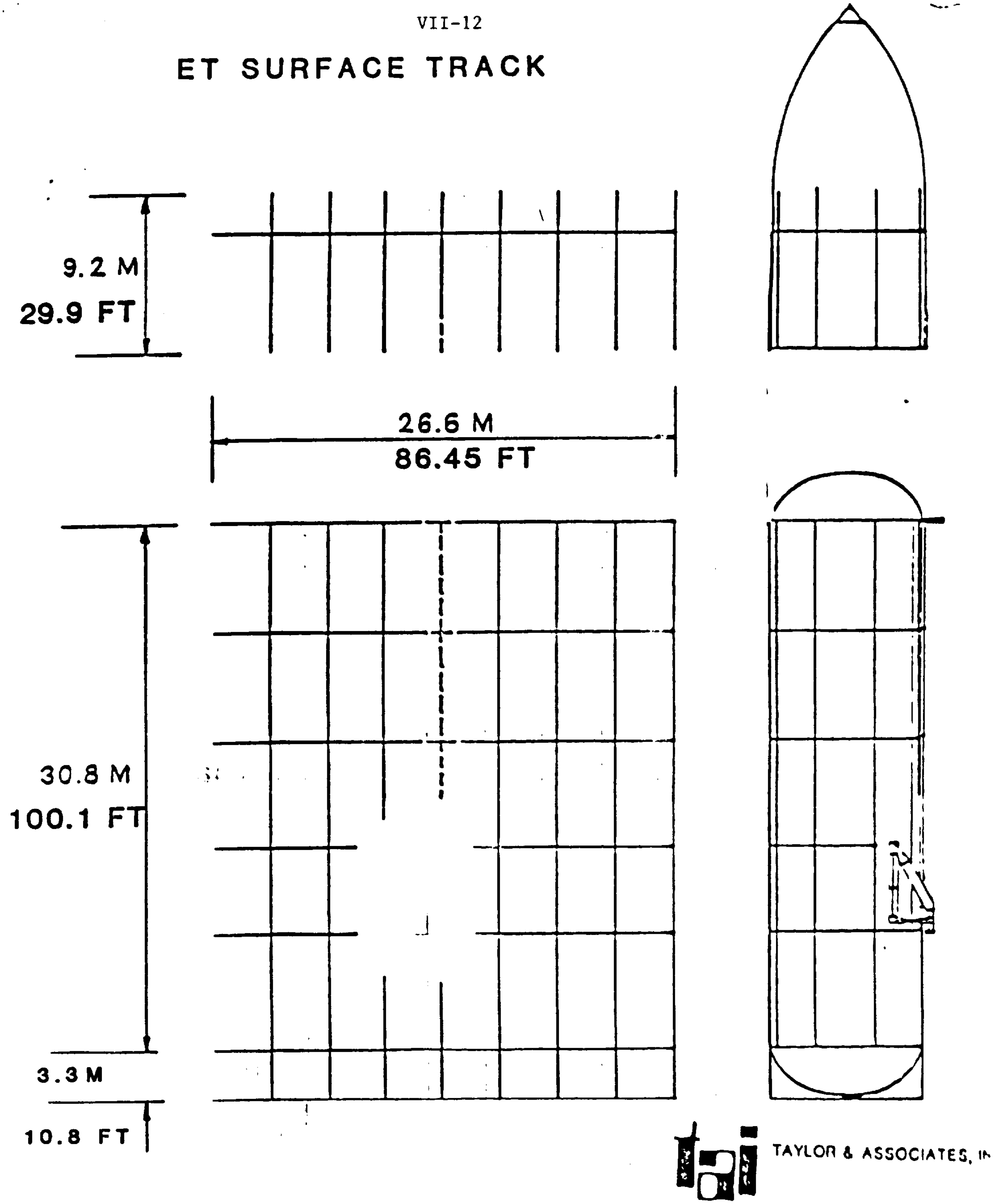

FIGURE 1

A POSSIBLE SURFACE TRACK SYSTEM FOR THE ET

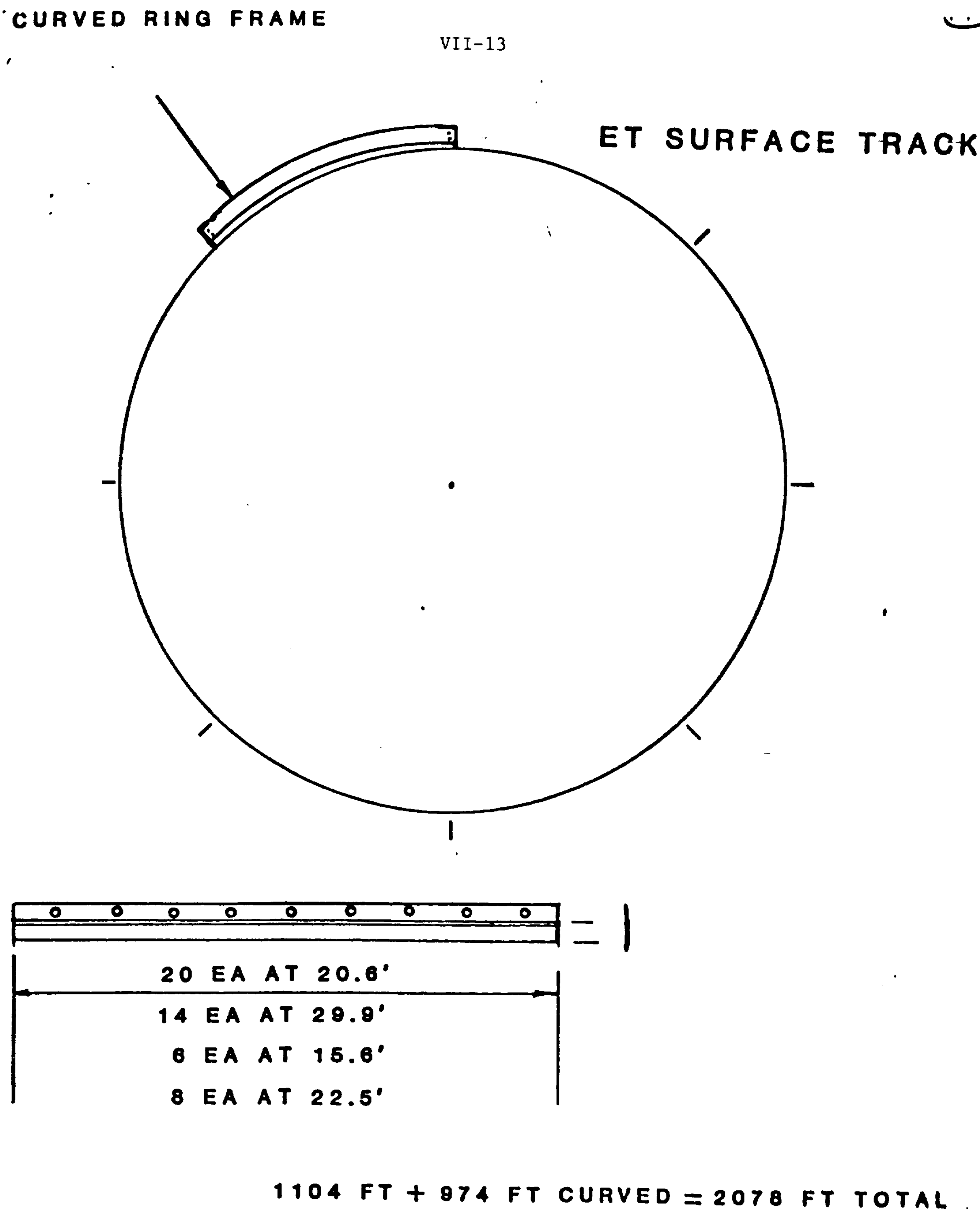

FIGURE. 2

SOME DETAILS OF PROPOSED TRACK SYSTEM

VIII. LIFE SCIENCES AND LIFE SUPPORT
(Uses of "Bottles" in Space)

A. Introduction and Recommendations

In this section we examine a number of possible uses in space for large "bottles" such as those provided by an orbiting External Tank (ET). We will concentrate, in particular, on uses pertaining to Life Sciences and Life Support. The following recommendations are the results of this initial investigation.

1. A study should be made of the possible emergencies which might threaten the lives of astronauts in space. The ways in which a Shuttle External Tank (ET) might be converted into an Emergency Orbital Habitat should be examined in more detail.

2. Possible uses of large amounts of water, stored for long periods in an ET, should be studied. These uses might include commercial pharmaceuticals processing and various chemical experiments in space.

3. Uses of the ET in support of biomedical, space biology, and advanced life-support research deserve further investigation. In particular, the possibility of controlled, large-volume ecological experiments in space should be pursued.

4. The results of this section add support to recommendations made elsewhere; that recovered propellants can be of great value; that possible modifications to the ET, to allow greater access (in space) to the tanks, are worth study; and that incorporation of the ET into space-station designs appears to offer long-term benefits.

B. Capabilities and Available Services.

The ET consists essentially of two closed vessels each designed to contain pressures up to two atmospheres. Many of the potential applications of the ET described elsewhere in this report call for disassembly and alteration of the tanks in orbit. Some possible uses, however, may require only minimal modifications, taking advantage of the tanks' chief attribute, as large pressure vessels.

The two main features of this section deal with Emergency Habitats (Part D) and Biology and Life Support (Part F).

Available Volumes

-ET liquid oxygen tank -- 147,000 gallons
($552\ m^3$; $19{,}9495\ ft^3$)

-ET liquid hydrogen tank -- 405,000 gallons
($1{,}523\ m^3$; $53{,}800\ ft^3$)

The availability of such large bottles in orbit immediately suggests a variety of possible uses. Some, such as development of the enclosed volumes into space station components, are dealt with elsewhere in this report. Here we shall discuss some potential uses which apply to Life Sciences and to Life Support. These fields have in common a shared interest in air-tight containers in orbit, in which gases and liquids can be stored and used.

Depending on cargo launch-weight, an orbiter plus ET combination will enter Earth orbit with at least 10,000 lbs, and as much as 50,000 lbs, of excess hydrogen and oxygen propellants. These residuals are examined elsewhere in this study, especially insofar as they might be used as propellants for upper stage vehicles. The "bottle" uses described in this section also are expedited by saving excess hydrogen and oxygen. The uses will add to the demand for recovery and storage of volatiles in space, making a routine reclamation procedure desirable each time it is practial.

C. Storage and Waste Disposal

The enclosed character of the LO_2 and LH_2 tanks suggests using them to collect materials which might otherwise clutter a manned facility, or drift off as unrecoverable space-debris. An external tank, possibly linked to a Space Operations Center, can be used as a waste-dump, for instance. One-way valves or locks would allow astronauts to isolate waste materials in an essentially limitless volume. (It should be emphasized here, that what is considered "waste" one year might be next year's "recoverable resources.")

Tanks can also store large tools, parts for vehicles and devices assembled in orbit, and structural elements salvaged from other ETs.

A major product requiring storage is the 10,000 to 50,000 lbs of residual propellants recoverable from each orbit-inserted ET. The liquid hydrogen and oxygen can be used either as upper stage propellants, or as a high-rate power source, providing more than three weeks' orbiter electric power requirements, or extending the capabilities of a Spacelab.

The propellants themselves will have to be stored in separate cryogenic bottles, as part of a general recovery/storage unit. But one of the 550 cubic meter liquid oxygen tanks might be used to store water, especially if any appreciable amounts of hydrogen and oxygen are used in fuel cells.

If 10,000 lbs of recovered propellants are converted in fuel cells, more than 1,000 gallons of water are produced. The oxygen tank is thus capable of storing the leftover from 50-150 shuttle launches in which residuals are thus used.

Water storage might be part of a general power maintenance scheme for a Space Operations Center, in which cryogenic hydrogen and oxygen are used to supply high-rate electrical power when the station is manned, and solar cells provide low-rate energy to electrolyse and replace the cryogens from the water reservoir when the facility is unoccupied. Some techniques for cryogenic cooling and storage are discussed in other parts of this report.

D. Emergency Orbital Habitat

With the instituion of space logistic support facilities, the shuttle will frequently and regularly return to a set of standard orbits. With repeatability of orbits comes the possibility of an in-place emergency habitat. If economically feasible, it is desirable to have a place for astronauts to take refuge and await rescue in the event of a catastrophe. Minimal precautions could, one day, prevent a major disaster. The requirements for a minimal emergency habitat are:

- An airtight chamber,
- Simple access by astronauts,
- Air, water and power,
- Carbon dioxide and waste removal,
- Supply packets stored in space until needed,
- A communication system,
- Protection from the radiation environment.

All but the last of these needs are easily provided using one of the ET tanks in conjunction with a simple residual propellants storage/fuel-cell unit, and a small airlock/logistics module. In addition to the tank itself, the material needed for the habitat should take up only a very small portion of the shuttle cargo bay. The logistical packets could be carried up in a single flight, as spare cargo.

It should be a minor modification to prelaunch-modify the "manhole" access plates in the ET, or the nose cover of the oxygen tank, so that they may be removed by an astronaut in EVA and replaced by a simple airlock module. The general usefulness of such a capability is persuasively argued elsewhere in the report. Here we simple state that the technique is directly applicable to an Emergency Orbital Habitat.

If a cryogenic storage/fuel unit is already in place, for reasons mentioned above, it becomes a simple matter to provide <u>oxygen</u>, <u>water</u>, and <u>power</u> to a tank chosen as a refuge. These can be introduced via small plumbing modifications in the intertank, established prior to launch. (These small return lines may become semi-standard features, as we shall see, since re-introduction of water and oxygen is desired for almost all the "bottle-uses" described hereafter.) Using simple, manually controlled taps, possibly supplemented by small heater elements, an astronaut within the refuge would have access to the four most important ingredients of survival in space -- shelter, pressurization, oxygen, and water.

Even the smaller oxygen tank has a volume in excess of 550 cubic meters. With this large a volume, the carbon dioxide production of one astronaut will take at about a man-month to rise to 0.70 psi, at which point humans have difficulty maintaining consciousness under normal conditions. If the hydrogen tank were used instead, this time would be multipled by three. (The LH_2 tank has a 50% higher safety margin as a pressure vessel than the LO_2 tank. The figures for CO_2 buildup tolerance will vary somewhat with the atmosphere maintained.) Thus, in the minimal shelter design, simple volume inertia should suffice to protect astronauts from CO_2 poisoning long enough to allow a rescue mission to be organized and launched.

A small package of consumables, including LiOH cells, might extend this period greatly. With plenty of oxygen available, venting stale atmosphere into space is another possibility.

Even without physically entering the ET, astronauts could use this volume inertia capability. The atmospheric lifetime of a crippled orbiter would be extended tremendously by either the resources of, or the CO_2-absorbing inertia of the ET, depending on how the connections were implemented.

Thermal control appears to be possible in a number of ways, the simplest being down parkas, which can be highly effective when there is little or no convection. Sunlight may be introduced through a one meter diameter manhole or nose-cap, converted to a window. Fuel-cells or solar power can run heaters. Vented cryogenic oxygen can be quite effective to control excess heat.

The ET is, of course, a more than sufficient Faraday cage. Astronauts (and vital cargo) within a tank would be safe from electromagnetic pulse radiation.

So far, what we have described is an absolute minimum shelter concept -- efficient in its use of resources already on-hand, or already projected for other uses. As time passed, embellishments might be added to such a basic habitat, improving the man-rating of the structure and incidentally contributing experience that would apply to later space station concepts.

Protection from solar flare protons, for instance, requires much more shielding than that provided by either the orbiter or any proposed S.O.C. design. The ET offers a way to give astronauts a place of safety during solar proton storms, especially in polar orbits. A single ET that has been converted into an emergency habitat can be covered with layers of material taken from other ETs disassembled in orbit. Among the methods proposed -- the shelter might be coated with "shingles" of aluminum cut from tank-walls, or individual cylindrical hydrogen tanks might be split longitudinally and wrapped around the emergency habitat in layers.

An added benefit of such shelter designs would be the consolidation of the material of many tanks onto a single, low-drag body, lengthening the orbital lifetime of a very large mass of metal.

Specific shielding designs are less important, at this point, than the simple fact that orbit-inserted ETs could supply all of the mass needed for a radiation shelter, without cost to the shuttle lift-budget.

E. Chemistry and Pharmaceuticals

The use of inflatable bladders would allow accumulation, within the ET, of from 1,000 to 400,000 gallons of liquid water. Water being stored for longterm re-use as propellants can be used for other purposes in the meantime. These applications can take advantage of the low-gravity, solar ultraviolet, availability of vacuum, and substantial freedom from outside contamination.

The recovery of residuals from shuttle launch makes possible large-scale aqueous chemistry in orbit. Such endeavors would be prohibitively expensive if water were carried into orbit as cargo.

Of particular interest is production of pharmaceuticals in orbit. Recent encouraging experiments in electrophoretic separation of biological compounds in zero-gee could be made even more attractive if stock and pre-refined product did not have to be lifted in the shuttle.

Grinding up the ablative coating surrounding an ET might produce large quantities of small inert beads. Such beads might provide an extremely large surface area for adhesion by plant and animal cells for tissue-culture experiments. Such processes might benefit from weightless conditions, with cell cultures stirred and illuminated (artificially or by piped-in sunlight) in a water/nutrient mixture within a modified ET. The products might be extracted and refined in a separate orbital facility, and the liquids recycled.

Another type of chemical experiment, using the unique attributes of the ET, is the study of the photochemistry of planetary atmospheres. By filling the large volume of the ET with the appropriate gases, and channeling sunlight into the tank through a fused quartz window, the effects of ultraviolet radiation on large masses of exotic gas might be studied.

Among the possible experiments are:

- Modelling the atmospheres of Titan, Jupiter and Saturn, using hydrogen returned from the cryogenic propellants store, plus additional gases provided from small, orbiter-carried dewars.

- Studying the photochemistry of ozone.

- Preparing bottles containing various mixtures proposed to model the primordial atmosphere of the Earth, and studying the resulting pre-biotic compounds.

It is interesting to note that by burning the polyisocynaurate foam, used to insulate the ET during liftoff, one derives among other products, CO, N_2, and HCN. These happen to be strong candidates for primordial Earth-atmosphere constituents, and are of great interest in the astronomical photochemistry of comets and interstellar gases.

An additional gas-mediated experiment, which is mentioned elsewhere in the report, is the genre of ion-discharge studies, in which the paths of gamma rays and cosmic rays through large volumes would allow unsurpassed measurements of fluxes and vectors of high energy particles in near-Earth environs.

Finally, experience with liquid management in space can lead to development of advanced methods for the utilization of extraterrestrial resources. In particular, ET residuals might provide the bootstrap water required for aqueous chemical reduction of lunar soils, as studied by Waldron, Criswell, and others.

F. Biology and Life Support

The ET provides a potentially inexpensive resource to advance space biology and life support programs. Some requirements which must be met prior to initiation of biology and life support experiments include: a long term power supply and well controlled interior illumination, thermal control, availability of suitable chemicals and nutrients (H_2, O_2, H_2O, CO_2, and growth medium), access, the ability to retrofit the ET with the experiment packages, and pseudogravity, if desired.

The features of an ET which might be of particular biological interest include:

- access to water and oxygen (in conjunction with a residual fuels storage unit)
- an airtight container
- very large, uncluttered volumes

The ET provides a possible location for flight testing and qualification of large scale Advanced Life Support systems (ALS), such as those using Bosch or Sabatier reactors to regenerate atmosphere and recycle some waste products. Components are currently under contract for ground-based prototypes. McDonnell- Douglas has run a ninety day test of a semi-isolated Earth-based ALS system, for instance. Large scale in-situ testing may require the very services and volumes best provided by an ET-based system.

Once an ALS is flight qualified, the ET might be utilized for more advanced space biology experiments. The large external tank would allow examination of many varieties of plants or animals in space. Experiments would measure the effects of varied gravity and atmospheres upon plant and animal growth and reproduction. Under gravity-gradient induced "pseudogravity" (see "Tether" section) a medium composed of ground-up, inert ablator materials, plus a nutrient substrate and water, will settle to one wall of the tank, providing a composite much like "potting mix," for plant experiments.)

Biomedical and physiological experiments involving animals and people could be pursued under controlled gravities. The open area of the hydrogen tank would allow weightless time and motion exercises with greater freedom than in the orbiter. It has been suggested that the use of an ET as a counter-balanced centrifugal sleeping quarters might result in improvements in the cardio-vascular health of astronauts staying for long periods in space.

Compartmentalization of the ET by inflatable partitions might allow the study of many experimental CELSS environments simultaneously, for long periods of time. The problems of ecological maintenance in low gravity, with minimal outside support, could be studied exhaustively.

Successful experiments might be repeated without partitions, in the large volumes of ET bottles. These high-volume experiments might involve direct introduction of sunlight through a window port (replacing a manhole or nosecap), using a coelostat mirror-concentration system.

Both the ALS and the CELSS experiments suggest a "lifeboat" resource in addition to the simple scheme discussed in section D. Though such controlled biological experiments may be thrown out of balance if astronauts enter, the value of the CELSS tank as a reserve emergency shelter would merit further study. The possibility that such a multipurpose tank would extend the safety-time of astronauts awaiting rescue is worth pursuing.

Depending on the method used to stabilize the orbit of the ET, the experiments placed within will experience different amounts of "Pseudogravity" -- from thousandths of an Earth gravity, in the case of a single tethered ET, or 3% G or more in the case of an ET spinning about its long axis at one or more rpm. These available levels of acceleration will affect the design of the various bottle experiments.

At LEO, sunlight will strike ET at least 55% of the time. A simple window, replacing one of the 36" diameter manholes, will not generally be oriented sunward, however, a coelostat system, using a simple expandable mirror, could provide focussed sunlight to supplement interior artificial lighting. In the case of closed ecosphere experiments, provision would be made to prevent biological fouling of the windows.

G. Conclusions

The "bottle" uses described in this section appear to strongly support arguments for routine recovery of residual propellants from the Space Shuttle External Tank. They indicate that there might be many additional potential customers for the water, volatiles, and power that the residuals can provide.

Following is a set of areas of interest, which deserve further conceptual study:

- Use of the ET as an emergency habitat for stranded astronauts

- Isolation of waste materials in the large-volume external tank

- Storage of large amounts of water for multiple uses in space

- Use of large bottles for aqueous chemical and biological processing in space

- Large-scale study of exotic atmospheres at low-gravities, simulation of other planets' atmospheres, ozone photochemistry, etc.

- Using the ET as a gas-discharge chamber in which to study cosmic rays and other phenomena

- Use of the ET in support of biomedical, space biology, and advanced life support research

- Experiments in large controlled ecological systems

- Research directed toward ultimate development of systems to recycle waste, produce consumables (including food) in orbit, and extend the independent capabilities of man in space.

Toward these ends a number of issues should be addressed. It is proposed that future investigators should:

- analyze affordable degrees of pre-launch and on-orbit retrofitting, particularly where applied to ease EVA-replacement of manholes with orbiter-carried modules.

- study the stability of the ET as an experimental platform, including the effects of gravity gradients and parameters limiting investigator access.

- investigate long-term power supply (photovoltaics, etc.) needs, and the suitability of long-duration onboard, reversible fuel cells.

- describe the requirements "bottles" users share with other customers of the external tank, toward the development of common resources and techniques.

- characterize impacts on ET architecture, especially as regards the effects on STS production schedules.

- investigate the feasibility of returning the products on an onboard cryogenic storage/fuel-cell unit to either tank, enabling the provisioning of experiments and emergency habitats with oxygen, hydrogen, power, and water.

- develop functional requirements for large-scale biological, ecological, and life-support activities within an External Tank.

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APPENDIX I

WORKSHOP ON UTILIZATION OF THE EXTERNAL TANKS
OF THE SPACE TRANSPORTATION SYSTEM

A

23-27 August 1982
Muir College, UCSD

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* PLEASE NOTE: 619 is the new area code for SAN DIEGO County as of 6 November 1982.

APPENDIX I

ORGANIZATIONAL MEETING FOR AUGUST 1982 WORKSHOP
14 July 1982
CALIFORNIA SPACE INSTITUTE, SCRIPPS INSTITUTION OF OCEANOGRAPHY

B

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APPENDIX I

C

Preliminary Workshop on the Utilization of the External Tanks of the Space Transportation System

NASA/California Space Institute
8-9 March 1982

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Appendix II

ON A NEW CONCEPT FOR A SPACE STATION ARCHITECTURE

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ON A NEW CONCEPT FOR A SPACE STATION ARCHITECTURE

INTRODUCTION

In the past six months we have received comments on our idea of a two level gravity gradient space station made by connecting two sets of external tanks (e.t.) with a number of cables several tens of km long (see SAO Technical Note TP82-04). The general concept for such a structure was originally considered very favorably at various levels of NASA; so favorably, in fact, that we have been encouraged to develop the idea further. We will refer to our report "A Straightforward Use of External Tanks" which was not fully inserted in the Arnold Report (Arnold, 1982) because of the length of the report, and because only a very preliminary concept had been defined. For reasons of simplicity, we will refer to it s C.S.'82 from now on, which stands for Colombo, Spring, 1982. We have also received several discouraging comments. Some are due to misunderstanding of the general philosophy leading to the concept and some are based on political arguments (government policy, DOD policy, industrial policy). In the pages which follow we will try to take these comments into account and to be more clear. Discussion with people of various backgrounds led us to think that the main difficulty is related to the fact that most people are not familiar with the principles of celestial mechanics. They are less familiar with those principles than we are with the technology, economics and operation of the Shuttle. In particular, many people are not familiar with the natural dynamics of large bodies in orbit. To those who do understand the dynamics and have appreciated the concept, we address the following pages in consideration of their honest criticism and the proper questions they raised, most of which we did not have the time and the means to consider in C.S.'82. In the following sections are going to (1) reconsider first the general philosophy of the concept, (2) study in more detail one possible configuration using 15 tanks, (3) study the operation of such a system as a S.T.S. operation center (dynamic stability, dynamic behavior during docking and undocking with the Shuttle and following launching or retrieval of a payload with or without an Orbital Transfer Vehicle (OTV)), and (4), study the assembly of the basic elements and complete structure.

1. GENERAL PHILOSOPHY AND RELATED ASSUMPTIONS

We will first recall a few assumptions which we have made, taking into account only the technical aspects. (a) The present S.T.S. with spinning upper stage, and possibly with the Centaur, is marginally competitive against Ariane. (b) Keeping time schedules will become more and more difficult when assembling a complete Shuttle payload defined years in advance. (c) The same comment is valid for assembling several payloads to be transferred directly to GEO with the OTV. (d) Bringing the e.t.'s to orbit does not cost anything and is actually more economical than the current procedure. (e) To be effective, a space operation center supporting the S.T.S. has to satisfy the following requirements:

1. High stability.
2. Large mass (at least several times the Shuttle mass).
3. Long lifetime (a typical orbit above 450-500 km altitude).
4. Not require a complex docking with the Shuttle in terms of maneuvering.
5. Provide a comfortable environment for humans.
6. Provide a clean environment for research (science and applications).
7. Be a medium-long term project which may begin to be an operational facility in the 90's.
8. Start as a medium size facility (300-500 ton) and grow, possibly in 10 years, to a larger dimension (1000-1500 ton) with a decrease in the cost per ton of mass increase.
9. Lead in 20 years to a space operation center that will drastically reduce the operational cost of the S.T.S. both from ground to low earth orbit and from low orbit to geostationary, lunar and interplanetary orbit.

Some of these assumptions may not be considered valid by everyone but they are the result of a large number of discussions with people who are thoroughly familiar with the Shuttle. The basic assumption here is that we are going to live with the Shuttle as it is, or with slight modification, for the next generation (25 years). If this is the case our assumptions cannot be very far from reality.

In Section 4 we will list the comments and criticisms we have received in regard to the space station architecture proposed in C.S.'82. We shall respond to them in the sections that follow Section 4. First, however, we will include two brief sections of C.S.'82 that summarize our concept of a space station architecture based on the e.t.'s. The completed structure is assumed here to utilize 50 e.t.'s.

2. CONCEPTUAL DESIGN OF AN EXTERNAL TANK SPACE STATION

In Figure 1, we have an example of a large symmetric space station in its final configuration. Two parallel planar assemblies of 25 External Tanks are linked by 6 cables each 20 km long. Each cable is a woven Kevlar rope, protected against ultraviolet radiation, with a diameter of 0.5 cm and working at less than 50 kg/mm^2. The number of connecting cables may be increased to 8 or more if necessary for safety reasons.

The mass at each end is on the order of 900 metric tons. The External Tank arrangement is designed to minimize the cross-sectional area in the direction of motion. The 6 or 8 ropes connecting the two platforms may also be connected among themselves with a few structural elements and, possibly, dampers to assure system stability.

In the steady state configuration the main cables are aligned with the vertical while the two platforms are horizontal with the long side parallel to the orbital plane. The short sides are normal to the velocity vector.

3. MAIN FACILITIES AND APPLICATIONS OF THE STATION

The lower platform, where the acceleration is 4.5 cm/sec^2 and one ton could be lifted with 10 pounds of force, may be used as a space operations center. Actually the Shuttle may land on the lower platform, or deliver an external tank for fuel transfer. A pressurized habitat facility may also be placed in or on the lower platform. Fuel storage areas, assembly areas (pressurized or unpressurized) and a small engine for station keeping, orbital maneuvering and attitude control could all be located on the lower platform.

An elevator for both men and equipment moving from the lower to the upper platform is also envisaged. This elevator may provide the most efficient way of getting a variable gravity field about zero-g, which reverses when passing through the center of gravity of the space station. A material processing facility may be incorporated in the elevator to take advantage of the zero-g condition. The upper platform will be dedicated to science and applications. We wish to keep the environment around the upper level as clean as possible to assure clear viewing for scientific instruments.

Both the upper and lower platforms will be equipped with tether type deployers with large mass capability. The upper deployers will have several hundred km of cable and may be used for launching and retrieval of spacecraft. The lower deployer of length 200-300 km, may be used for supporting ground-to-orbit transfer and re-entry.

A few examples may be in order here. Suppose we have to transfer a payload from the platform to ground safely. Assuming the platform is at 450 km altitude or higher, we may transfer the payload with a cable to 150 km altitude with a velocity of 0.5 to 1 km/sec smaller than the normal re-entry velocity. Suppose we want to launch a spacecraft to a geostationary orbit or an interplanetary trajectory. We may use the upper deployer gaining several hundred m/sec velocity which may correspond to increasing the square of the escape velocity (C_3) by 10 to 20 km²/sec². A detailed study of this concept has already been done by us in association with a research group at MIT. The usefulness and flexibility of such a system in many applications is very high and its feasibility has been demonstrated (see Figure 2).

4. COMMENTS

We list here some of the comments which we believe deserve serious consideration.

4.1 The C.S.'82 architecture does not solve the problem of the space station in the short term. In particular, the large number of e.t.'s to be carried and assembled in orbit will absorb financial resources which may be otherwise dedicated now to the space station.

4.2 The space station as conceived in C.S.'82 does not have enough mobility and is therefore a very vulnerable object.

4.3 The low gravity field (typically 0.01g) is not sufficient to provide a comfortable environment for men and does not simplify operations.

4.4 Dynamic stability in the normal operation mode is inadequate. In particular, in-plane and out-of-plane librations, torsional librations, longitudinal vibrations, and wave propagation along the cable have been mentioned. The phrase normal operation mode here refers to all operations with the exclusion of the transient events related to docking and undocking with the Shuttle or the release or retrieval of heavy payloads.

4.5 The dynamic response of the structure to docking and undocking of the Shuttle or the transfer of heavy payloads is a serious problem.

4.6 In a docking maneuver of the Shuttle with the space station, there are questions concerning the time scale and complexity of maneuvering, the opportunity for docking and the amount of fuel consumption. The main concern is the following: if the docking maneuver fails, when will the next opportunity be for docking.

We will present our response to these comments in the following two sections.

5. DISCUSSION OF CONCEPTUAL AND ENVIRONMENTAL COMMENTS

Comment 4.1 was the first we heard. Surely we did not intend to solve the problem of the space station in the short term, if by short term one means 1985-1990. We do not see any possibility (considering present political and budgetary constraints) that a space station will be operational in this time frame without a large financial effort (new start) beginning in 1983. The second point we would like to make is that the type of enterprise we are suggesting need interfere in only a modest way with the development of a space station of smaller dimensions, especially if the type of space station we propose is built with, say, only 15 e.t.'s. The third point we want to make is that the cost of the structure represents a relatively low fraction of the total cost in any case, while the proposed structure may reduce the complexity of both the necessary equipment and its operation and therefore the total cost. It may be worthwhile to emphasize again that what we are proposing is an economical way to preserve the energy, angular momentum, mass and material of the e.t.'s in orbit for future exploitation. The possible exploitation of the e.t.'s in the manner proposed is extremely attractive.

Comment 4.2 is related to the role the space station is supposed to play in the defense-offense system of the nations which have achieved a high level of sophistication in space technology. It seems to us that the alternative of having a set of mobile small space stations in space is equally vulnerable and considerably more expensive. On the other hand, we are concerned with the possibility of building a multipurpose civil system and eventually a system suited for international cooperation in the broadest sense. We will emphasize this concept later in dealing with technical aspects of the kind of space station we propose. In any case, the strategy of an offense-defence system in space seems to be still very foggy and very unpredictable. The question is reminiscent of the argument raised recently against the large aircraft carrier in relation to its vulnerability.

Comment 4.3 was the most surprising to us and we could not believe it was serious. We can think of only one way to respond to the comment and that is to ask what the alternatives are. Is it reasonable to consider giving up the possibility of using the small gravity field for transferring liquids, for assembling components, for storing objects in an orderly way, for men to move around, and so forth?

6. DISCUSSION OF COMMENTS ON DYNAMICS

A few years ago one of the authors (G. Columbo) gave the Hunsaker Lecture at M.I.T. on "Evolution of Space Technology, Fiction vs. Reality." It started in the following way:

"'Ladies and Gentlemen, there is no one among us who has not gazed long and carefully on the moon, or at least who has not heard of those that have.' With this phrase, Barbicane, the President of the Gun Society of Baltimore, began his communication in October 1965 as reported by Jules Verne in his book 'From the Earth to the Moon.'"

We were tempted to begin here with the same phrase. The moon is in fact an example of a large space station stabilized by the earth gravity gradient, by the tides raised by the earth on an elastic dissipative moon.

Naturally our space station is smaller but it is much closer to the earth, more elastic and (can be made) more dissipative while the inertia tensor may be adjusted to increase the stability of the configuration. The basic laws which control the motion of the moon, Cassini's laws, will hold here too due to the large departure of the inertia ellipsoid from an axially symmetric shape. In one of the following sections we will deal specifically with the problem of the dynamics of the steady state.

The dynamics of the system will also be considered in the following sections taking advantage of analyses which have been done in the last five years of the tethered satellite system. We also have studied a dumbbell gravity gradiometer which has the same general configuration of the space station. Torsional motion of the system will be analyzed following the same technique.

Before passing to the dynamical analyses we will in the next section describe a system with the minimum mass and dimensions required for operational efficiency and that would require only 15 of the e.t.'s. We will then respond to Comment 4.6 in Sections 6.2 and 6.3 and to Comments 4.4 and 4.5 in Section 6.4.

6.1 A Space Station Utilizing 15 E.T.'S

Let us consider two masses M, m connected with a system of cables of length h, in circular orbit in a gravity gradient stabilized configuration. Let G be the center of mass of the system and a_0 the semi-major axis of a reference parking orbit of the shuttle (a_0 = 6600 km). We call $a_0(1+\varepsilon)$, $a_0(1+\varepsilon-\sigma)$, $a_0(1+\varepsilon+\beta)$ the radii of the orbit G, m, M. The following relations hold:

$$h = a_0(\sigma+\beta), \quad \sigma = \frac{M}{M+m}\frac{h}{a_0}, \quad \beta = \frac{m}{M+m}\frac{h}{a_0} \tag{1}$$

We will assume the particular case of M = 400 ton while for m we will assume a value of 130 ton, giving a mass ratio value of 3. The architecture of the system is of the same type as the asymmetric space station given in C.S.'82 and shown here in Figure 3. The number of tanks needed will be 15. A possible configuration of the system is shown in Figure 4.

We want to analyze the system as a support for the S.T.S. We begin by considering the relationship between the first order infinitesimal quantities ε and σ, which does not depend on the choice of mass or dimensions of the two platforms.

We consider the Shuttle in an eccentric transfer orbit with perigee a_0 and apogee $a_0(1+\varepsilon-\sigma)$. The lower level platform is in a circular (non-natural) orbit; only G is in circular natural orbit (see Figure 5).

If we call v_c^* the velocity of the Shuttle in the parking orbit (circular with radius a_0 and mean motion n_0) we have:

$$v_c(G) = v_c^*\left[\frac{1}{1+\varepsilon}\right]^{\frac{1}{2}} = v_c^*\ (1 - 1/2\ \varepsilon)$$

$$n_c(G) = n_0\ (1 - 3/2\ \varepsilon) \tag{2}$$

The velocity of the Shuttle in the transfer orbit is:

$$v_{per}(s) = v_c^*\left[\frac{2(1+\varepsilon-\sigma)}{2+\varepsilon-\sigma}\right]^{\frac{1}{2}} = v_c^*\ [1 + 1/4\ (\varepsilon-\sigma)] \tag{3}$$

at perigee, and

$$v_{ap}(s) = v_c^*\ [1 + 1/4\ (\varepsilon-\sigma)]\ \frac{1}{1+\varepsilon-\sigma} = v_c^*\ [1 - 3/4\ (\varepsilon-\sigma)] \tag{4}$$

at apogee. The velocity of the lower platform m is:

$$v(m) = v_c(G)\ \frac{1+\varepsilon-\sigma}{1+\varepsilon} = v_c(G)\ (1-\sigma) = v_c^*\ (1 - \varepsilon/2 - \sigma) \tag{5}$$

We want the Shuttle to arrive at the lower platform with zero relative velocity and therefore:

$$v_c^*\ (1 - \varepsilon/2 - \sigma) = v_c^*\ (1 - 3/4\ \varepsilon + 3/4\ \sigma) \tag{6}$$

That implies:

$$\sigma = 1/7\ \varepsilon \tag{7}$$

To illustrate this result, we assume $\varepsilon = 0.05$ and $a_0 = 6600$ km. We have $\varepsilon a_0 = 330$ km and, from equation 7, $\sigma = 0.007143$ and $\sigma a_0 = 47.15$ km. The apogee of the transfer orbit and the radius of the circular orbit of m is 6882.85 km and the eccentricity of the Shuttle orbit is $(\varepsilon-\sigma)/2 = 0.02143$.

For a mass ratio $M/m = 3$, we will then have $\beta a_0 = 15.716$ km and the total length of the cables connecting the two platforms will be 62.86 km. The gravity field at the lower platform will be

$$3g(G)\ \frac{\sigma a_0}{a_0(1+\varepsilon-\sigma)} = 3 \times g_0\ \frac{\sigma R_\oplus^2}{a_0^2(1+\varepsilon-\sigma)^3} = 0.0176 g_0\ , \tag{8}$$

which is 17.2 cm/sec², while at the upper platform the gravity field is $0.006 g_0$ or 5.77 cm/sec². The total tension on the cables at the lower platform is $0.0176\ m g_0$ which is about 2 ton force if $m \sim 130$ ton.

6.2 The Docking Problem

Here we will make a preliminary assessment of the docking problem. The first question is the following: given a maximum value Δv_{max} for the difference in velocity Δv and a maximum value δ_{max} for the distance δ of the two spacecraft, the Shuttle and the lower platform, what is the length of the time interval for which $\delta < \delta_{max}$ and $\Delta v < \Delta v_{max}$. In other words, given an interval of time that is short compared to the orbital period but reasonably long for a docking maneuver, what are the values of δ and Δv for the nominal trajectories as a function of time.

Since $n_0(1 - 3/2\ \varepsilon)$ is the mean motion of G and of the lower platform, the equations of motion of the lower platform are:

$$\rho_m = a_0\ (1+\varepsilon-\sigma) = a_0\ (1 + 6/7\ \varepsilon) \tag{9}$$

$$\lambda_m = n_0\ (1 - 3/2\ \varepsilon)\ t \tag{9²}$$

Here ρ_m and λ_m are the radius vector and true anomaly of m, respectively, and t is measured from the instant of nominal docking. The equation of motion of the Shuttle near the nominal docking point is the following:

$$\rho_s = \frac{a_0\ [1 + (\varepsilon-\sigma)/2]\ [1 -(\varepsilon-\sigma)/2]}{1 + [(\varepsilon-\sigma)/2]\ \cos\lambda_s} \tag{10}$$

and, to the second order in ε,

$$\lambda_s = n_0\ [1-3/4(\varepsilon-\sigma)t] - 2\ \frac{\varepsilon-\sigma}{2}\ \sin(n_0[1-3/4(\varepsilon-\sigma)]t) + 5/4\ [(\varepsilon-\sigma)/2]^2\ \sin n_0[1-3/4(\varepsilon-\sigma)]t$$

and (10²)

$$\rho_s = a_0[1 + (\varepsilon-\sigma)/2] \left[1 + \frac{\varepsilon-\sigma}{2}\cos\ (n_0[1-3/4(\varepsilon-\sigma)]t) - 1/2\ [(\varepsilon-\sigma)/2]^2\ \cos\ (2n_0[1-3/4(\varepsilon-\sigma)t]-1)\right]$$

If we take into account only first order terms in ε and substitute $1/7\ \varepsilon$ for σ we have

$$\begin{aligned} \lambda_s &= n_0\ (1-9/14)\ t - 6/7 \sin n_0 t, \\ \rho_s &= a_0\ [1 + 3/7\ \varepsilon(1 + \cos n_0 t)]. \end{aligned} \tag{11}$$

We may easily check that

$$\begin{aligned} \rho_s(o) &= \rho_m(o) = a_0(1 + 6/7\ \varepsilon), \quad \lambda_s(o) = \lambda_m(o) = 0 \\ \rho_s(o) &= \rho_m(o) = 0, \quad \lambda_s(o) = \lambda_m(o) = n_0\ (1 - 3/2\ \varepsilon). \end{aligned} \tag{12}$$

The distance (s,m) is given by

$$\delta = [\rho_s^2 + \rho_m^2 - 2\rho_s\rho_m \cos\ (\lambda_s-\lambda_m)]^{\frac{1}{2}} \tag{13}$$

Neglecting second order quantities in ε, from (9²) and (11) we get,

$$\lambda_m-\lambda_s = 6/7\ \varepsilon(\sin n_0 t - n_0 t). \tag{14}$$

Since, therefore, cos $(\lambda_m-\lambda_s)$ differs from one by a second order quantity in ε, we have finally

$$\delta \simeq \rho_m - \rho_s = 3/7\ a_0\varepsilon\ (1 - \cos n_0 t), \tag{15}$$

and

$$\dot{\delta} = 3\varepsilon/7\ n_0 a_0 \sin n_0 t\ . \tag{16}$$

In Figures 6 and 7 we plot values from equations 15 and 16, respectively, for the example we considered above: a_0 = 6600 km, n_0 = 16.1833 rev/d, ε = 0.05 (σ = 0.007143), εa_0 = 330 km, σa_0 = 47.15 km.

From -300 sec to +300 sec, $\lambda_m-\lambda_s$ goes from -3.2×10^{-4} rad ($-0\overset{\circ}{.}0183$) to $+3.2\times10^{-4}$ rad ($+0\overset{\circ}{.}0183$) while $\rho_m-\rho_s$ goes from 8.85 km through zero and increases again to 8.85 km. In the mean time, $\rho_m(\lambda_m-\lambda_s)$ varies from -2.1 km to +2.1 km. This means that neglecting second order terms in ε is not justified for intervals of time larger than 10 minutes centered on the nominal docking point. In particular, the value of δ given by equation 16 may be slightly smaller than the actual value (few percent). From equation 16 we have δ = 58.2 m/sec at t = $\pm300^s$ which may be considered large. If instead we consider the interval of time (-180^s $+180^s$) we have $\Delta(\lambda_m-\lambda_s)$ = 7×10^{-5} and $\Delta\rho_m(\lambda_m-\lambda_s)$ = 0.457 km, $\Delta\delta$ = 3.2 km while the maximum relative velocity is 37 m/sec. The approximation becomes even more precise in the interval (-120^s + 120^s), $\Delta(\lambda_m-\lambda_s)$ = 2×10^{-5}, $\Delta\rho_m(\lambda_m-\lambda_s)$ = 0.140 km, $\Delta\delta$ = 1.43 km while the maximum relative velocity is 24 m/sec.

6.3 Transfer Orbit Time Windows

Here we consider the problem of docking from the point of view of time windows for the Shuttle injection in transfer orbit from the parking orbit to the lower platform.

First we notice that 10 minutes seems to be a sufficient interval of time for the docking maneuver assuming that a Δv of the order of 50 m/sec is provided for this purpose by the Shuttle O.M.S. (orbital maneuvering system). We think therefore that a docking failure should be considered as an abort mode.

We consider now the configuration (most common or most interesting from the civil point of view but not necessarily from the D.O.D. point of view) of the Shuttle in a parking orbit circular at 220 km altitude and 28° inclination with the space station at the same inclination at 550 km altitude.

The transfer orbit for the configuration described in section 6.1 has a semi-major axis of 6741.4 km and an eccentricity 0.021428. In the table below (Table 1) the orbital elements a and e are given along with the mean motion n and the secular variations of the ascending node Ω and of the argument of perigee ω for an inclination of 28°. Note that for a configuration in polar orbit the nodal line does not regress while for an equatorial configuration the problem of differential motion of the orbital plane does not exist. For an inclination different from 0° or 90° the injection window is mainly constrained by the differential motion of the node.

Table 1

	a(km)	e	n(rev/day)	$\dot{\Omega}$(°/day)	$\dot{\omega}$(°/day)
Shuttle in P.O.	6600	0	16.1833	−7.8151	0
Space Platform	6930	0	15.0419	−6.57713	0
Shuttle in T.O.	6741.4	0.021428	15.6771	−7.25045	11.89860

Consider the case of 28° inclination illustrated in Table 1. The differential regression of the node between the Shuttle parking orbit (P.O.) and the Space Platform orbit is 1°.238/day, or 0°.0765 per orbital revolution of the Shuttle. In order to compensate for such a variation in one revolution, we need to change the orientation of the Shuttle velocity by 0°.0359 or 6.26×10^{-4} rad which implies a Δv of the order of 4.89 m/sec. This fact has a direct effect on the overall operational planning of the Shuttle launch from ground to low earth orbit and from low earth orbit to the transfer orbit or directly from ground to the transfer orbit. The Shuttle cannot be allowed to coast in the parking orbit for more than a few revolutions nor can a direct launch be similarly delayed without requiring out-of-plane orbital maneuvering.

Launching from ground to P.O. may be operated only in two possible windows per day which have to satisfy the two conditions: a) the orbital plane of the space station has to be close to the launch site and b) the space station has to be located within a proper range of longitude at the time of launch. One should notice that the problem we have discussed above is a general problem of the transfer from ground to any space station, and is not related in any way to the special architecture we propose. We shall therefore not discuss the docking problem in relation to the orbital plane any further but only emphasize again the particular advantages of a polar or equatorial orbit for a space station, the latter one being operated from an equatorial site.

The difference between the docking operation in the usual concept of the S.O.C. and our concept is that in the usual concept the Shuttle is transferred by the O.M.S. in the same natural orbit of the S.O.C. and may therefore spend a practically indefinite time for docking. In our case the operation has to be done in a relatively short time.

If the docking can not be performed within one close approach the orbit should be corrected in order to get a new rendezvous with low relative velocity within a few orbital revolutions. This operation has to be considered as an abort mode and a sophisticated maneuver optimization analysis is required which we are not in a position to do here.

The orbital plane, the apsidal line and the time of perigee passage have to be properly modified with the minimum use of the O.M.S. to achieve another close approach in the shortest time. This process is simplified for 0° or 90° inclination. In this case a straightforward solution is represented by the Shuttle returning to the parking orbit and waiting for the next opportunity which will certainly occur within roughly one day.

Moreover, the Shuttle may be initially injected in an orbit with a mean motion that is a rational fraction of the mean motion of the space station, which would permit additional rendezvous opportunities without returning to the parking orbit. In a particular case, if the mean motion of the transfer orbit were 15.6686 rev/day, 25 revolutions of the Shuttle would exactly equal 24 revolutions of the space station. Thus, there would be a rendezvous opportunity every 38.5 hours not requiring any extra Δv. However, keeping the system under control may be less economical in terms of O.M.S. fuel than modifying the Shuttle transfer orbit in fewer revolutions.

In the case of a 28° inclined orbit, an out-of-plane Δv of 74 m/sec per day would be required to compensate for the differential regression of the node.

In conclusion, the proposed architecture does not appear to pose any new insurmountable problem from the point of view of the rendezvous maneuver with respect to the problems posed by the usual S.O.C. conceptual design.

We end this section by noticing that, whatever the stability of the lower platform, it is likely to simplify the docking maneuver substantially. We will discuss this matter in the following sections.

6.4 Dynamics of Docking

In this section we will present some considerations relative to the dynamics of docking. Let us consider the space station to be in a circular orbit with its center of mass G at 6930 km altitude. When the Shuttle docks with the lower platform, the overall system will change. The velocities of the various parts of the space station will all be the same, while the center of mass will be different. Assuming that the system is rigid, in first approximation, one may compute the orbit of the (new) center of mass G'. In fact, energy and angular momentum preservation give both the new semi-major axis and eccentricity of the orbit and the ensuing libration amplitude of the system. First let us compute the position of the new center of mass assuming that the mass of the Shuttle with the cargo is just equal to the mass of the lower platform.

Since h is the length of the cable we will have

$$G'M = \frac{M}{M+2m}\, h \;, \quad G'm = \frac{2m}{M+2m}\, h \tag{17}$$

The new coefficients σ', β' will be

$$\sigma' = \frac{M}{M+2m}\,\frac{h}{a_0} \;, \quad \beta' = \frac{2m}{M+2m}\,\frac{h}{a_0} \tag{18}$$

and if we assume $M = 3m$ we have $\sigma' = 3/5\ h/a_0$, $\beta' = 2/5\ h/a_0$. The new center of mass will be 37.716 km from the lower platform and 25.144 from the upper platform. Neglecting second order quantities, the velocity of G' will be

$$v_{G'} = n_0 a_0 (1-\varepsilon/2-\sigma+\sigma') \tag{19}$$

and since $\sigma = 1/7\ \varepsilon$, $\sigma' = 4\sigma/5$ we find

$$v_{G'} = n_0 a_0 (1-37/70\ \varepsilon) \;. \tag{20}$$

The local circular velocity is similarly found to be

$$v_{G'}^{(c)} = n_0 a_0 (1 - 34\varepsilon/70) \ . \tag{21}$$

Let us call $a_0(1+\varepsilon_a)$, $a_0(1+\varepsilon_p)$ the apogee and perigee distances of the orbit of G'. G' will be at apogee immediately after the docking. From the simple relation

$$v_{G'} = v_{G'}^{(c)} \left[\frac{2(1 + \varepsilon_p)}{2 + \varepsilon_p + \varepsilon_a}\right]^{\frac{1}{2}} , \tag{22}$$

we find

$$(v_{G'}/v_{G'}^{(c)})^2 = 1 + (\varepsilon_p - \varepsilon_a)/2 \ . \tag{23}$$

Since $\varepsilon_a = 34\varepsilon/35$ we have

$$\varepsilon_p = \varepsilon_a + 2[(v_{G'}/v_{G'}^{(c)})^2 - 1] = 28\varepsilon/35 , \tag{24}$$

and the perigee distance will be 6864.0 km, while the orbital eccentricity of G' will be

$$e = \frac{3}{35}\ \varepsilon = \frac{3}{35}\ 0.05 = 0.00429 \ . \tag{25}$$

Let us now assume the system to be a rigid body and consider the dynamics about the center of mass. Call A, B, C the moments of inertia of the system. C is the moment of inertia with respect to the axis normal to the orbital plane and may be taken as

$$C = \frac{2mMh^2}{2m + M} \ . \tag{26}$$

A is the moment of inertia with respect to the longitudinal axis and will be very small in comparison with C. B on the other hand will be almost equal to C.

The equation for the in-plane libration of the system is the following

$$\ddot{\theta} + \frac{3}{2}\, n'^2\, \frac{a'^3}{\rho'^3}\, \sin 2(\theta + u - n't) = 0 , \tag{27}$$

where u, a' and n' are the true anomaly, semimajor axis and mean motion of G', while θ is the angle between the longitudinal axis and an axis rotating in the orbital plane with the mean motion. For small ε we have

$$\begin{aligned} a' &= a_0(1 + \frac{31}{35}\varepsilon) , \\ n' &= n_0(1 - \frac{93}{70}\varepsilon) , \\ u &= n't - 2e \sin n't \ . \end{aligned} \tag{28}$$

For the eccentricity given by equation 25 we may write

$$\rho'^3 = a'^3(1 - 0.01287 \cos n't) , \tag{29}$$

and equation 27 becomes

$$\ddot{\theta} + \frac{3}{2} n'^2 (1 - 0.0129 \cos n't) \sin 2(\theta + u - n't) = 0 . \tag{30}$$

Assuming the libration to be small, we have finally

$$\ddot{\theta} + 3n'^2 (1 - 0.0129 \cos n't) (\theta - 0.0257 \sin n't) = 0 , \tag{31}$$

which implies, again neglecting second order quantities:

$$\ddot{\theta} + 3n'^2 \theta (1 - 0.0129 \cos n't) = 0.0772 n'^2 \sin n't . \tag{32}$$

Equation 32 is a Mathieu equation. However, since we are far from resonance we may take the following as a good approximation to equation 32:

$$\ddot{\theta} + 3n'^2 \theta = 0.0772 n'^2 \sin n't . \tag{33}$$

The general solution of equation 33 is the following :

$$\theta = A \cos n'\sqrt{3}t + B \sin n'\sqrt{3}t + 0.0386 \sin n't . \tag{34}$$

The equation of the actual motion of the system after docking has to satisfy the proper initial conditions. Equations 27, 28, and 29 have been written assuming the origin of time t to be when the system is at perigee. The actual motion begins when the system is at apogee. Therefore, equation 34 has to satisfy the following conditions:

$$\theta(\pi/n') = 0 , \quad \dot{\theta}(\pi/n') + n' - 2\varepsilon n' = n_0 (1 - \frac{3}{2} \varepsilon) \tag{35}$$

or

$$\theta(\pi/n') = 0 , \quad \dot{\theta}(\pi/n') = - \frac{2\varepsilon n'}{70} = - 0.0014 n' . \tag{35'}$$

These conditions in turn imply:

$$\begin{aligned} A \cos \pi\sqrt{3} + B \sin \pi\sqrt{3} &= 0 , \\ - An'\sqrt{3} \sin \pi\sqrt{3} + Bn'\sqrt{3} \cos \pi\sqrt{3} + 0.0386 n' &= - 0.0014 n' , \end{aligned} \tag{36}$$

which determines the constants A = 0.0148 and B = 0.0126.

The undamped librational motion is composed of a forced libration due to the eccentricity of the orbit of amplitude 0.0386 rad = 2°.2 and frequency equal to the orbital frequency and a free libration with a period 0.577 times the orbital period and amplitude 1°.2. The free component may be rapidly damped out.

Assuming that the free libration is damped out after unloading 40 tons from the cargo bay, the Shuttle is ready to re-enter either directly to ground or to a parking orbit. Considering the small value (4.29×10^{-3}) of the eccentricity acquired by the space station after the docking procedure, the problem of a window for re-entry is rather trivial. In any event, the Shuttle is safely located on the lower platform and can remain there indefinitely.

The orbital phase angle and librational phase at which the Shuttle leaves the space station does, however, have some effect on the space station orbit after the operation. If the Shuttle could leave the lower platform while the space station is at apogee, the orbit of the space station after the operation will be close to circular as it was before the loaded Shuttle docked with the lower platform. A simplified parametric study may be readily made. No surprises are expected.

7. DRAG COEFFICIENT AND LIFETIME CALCULATIONS

7.1 Drag Coefficient

Satellite drag coefficients are usually computed under the assumptions of free-molecule flow, complete momentum accommodation (cosine law as opposed to lobular scattering) and complete or nearly complete energy accommodation at heights below about 400 km. It is also fairly common to assume the problem to be hyperthermal (i.e., to neglect the random motion of the atmospheric molecules). We will not attempt a complete review of the subject here but will discuss only certain aspects of the theory that have particular relevance to the e.t.'s and the estimation of their rates of orbital decay as a result of atmospheric drag.

We should first point out that cosine (Knudsen) law scattering is observed generally with surfaces that are either relatively rough or contaminated or which absorb incident molecules and that there is no reason to question the validity of this assumption with respect to the e.t.'s or, in fact, most satellite surfaces. That this momentum accommoaation is necessarily accompanied by complete energy accommodation (i.e., that the scattering is indeed diffuse) is not quite so clear. In fact, it is traditional in satellite drag analysis to assume complete or nearly complete energy accommodation at lower heights but to allow the accommodation coefficient to decrease with decreasing mean molecular weight at greater heights where helium rather than atomic oxygen becomes the dominant constituent. Thus, the drag coefficient is taken to be about 2.2 in the lower height range but increases significantly at greater heights. That the assumption of nearly complete accommodation at lower heights is not too far from the truth is testified to by the fact that in situ measurements of atmospheric density by neutral mass spectrometers and other instruments agree closely with those obtained from drag analysis. It should also be pointed out that this assumption is implicit in all current atmospheric models based on observed satellite drag.

7.1.1 Free-Molecule Flow

There is reason to question the assumption of free-molecule flow in computing drag coefficients for the e.t.'s at heights much below 300 km because of their large size.

The condition for free-molecule flow is usually expressed in terms of the Knudsen number λ_o/D, where λ_o is the mean free path of an atmospheric molecule and D is the linear dimension of the object, as

$$\lambda_o/D \gg 1. \tag{37}$$

For a satellite, which moves at a very high speed, this is not sufficient because the satellite is partially shielded from the free stream by the cloud of more slowly moving molecules that have been re-emitted from the surface. In this case, the condition for free-molecule flow is better expressed as

$$\lambda_o/D \gg v_i/v_r \tag{38}$$

where v_i is the speed of the incident molecules and v_r is the average speed of a re-emitted molecule. The ratio v_i/v_i can be approximated by

$$v_i/v_r = [1-\alpha(1-E_s/E_i)]^{-\frac{1}{2}} , \quad (39)$$

where E_s is the average kinetic energy of a molecule scattered with a velocity corresponding to the surface temperature, E_i is the energy of the incident molecules and α is the energy accommodation coefficient. For a circular orbit at a height of 200 km (v_s = 7.82 km s^{-1}) and a surface temperature of 273 K, this equation gives v_i/v_r= 3.3.

Concerning what is meant by '>>' in the above equations, it is usually assumed that a factor of 5 is the minimum value required to satisfy the condition for free-molecule flow. This factor is only barely realized with respect to the e.t. diameter at 200 km, where the mean free path is only a few hundred meters, and is only realized with respect to the length (= 5.6 x diameter) at about 250 km.

The assumption of free-molecule flow for even a number of assembled e.t.'s at heights above 300 km, where the mean free path is at least an order of magnitude larger than at 200 km, appears to be valid, however. We are, of course, primarily interested in the drag on the e.t.'s at heights above 300 km. In any case, the only consequence of a departure from free-molecule flow will be that our assumed drag coefficient is too large and that, therefore, our estimates of lifetime are too conservative.

7.1.2 Contribution of Lateral Area

The most significant thing about the drag coefficient of the e.t.'s is that the random motion of the atmospheric gas cannot be neglected when they are flown in an end-on orientation. Even at grazing incidence, some atmospheric molecules will strike the side surface as a result of the random motion of the gas. The number that strike unit area will only be a small fraction of those that strike the same area normal to the orbital motion. In the case of the e.t.'s, however, the lateral area is so large that the total number of molecules striking the sides of the tank will be roughly equal to the number that strike the end. The number of molecules impinging on unit area per unit time N_i can be computed from

$$N_i(\gamma) = n_i v_s \frac{\gamma}{2}[1 + \mathrm{erf}(\gamma S)] + \frac{1}{2S\sqrt{\pi}} \exp(1-\gamma^2 S^2) , \quad (40)$$

where γ is the cosine of the angle of attack and S is the molecular speed ratio, equal here to the orbital speed divided by the most probable molecular speed. From this we have

$$N_i(1) \simeq n_i v_s ,$$
$$N_i(0) \sim \frac{n_i v_s}{2S\sqrt{\pi}} \quad (41)$$

and

$$\frac{N_i(0)}{N_i(1)} \simeq \frac{1}{2S\sqrt{\pi}} . \quad (42)$$

For S = 7, equation 42 gives $N_i(0)/N_i(1)$ = 0.0403 and, since the lateral area of an e.t. is 22.4 times the end area, the total number of molecules impinging on the sides is 90% of the number impinging on the end.

The molecules impinging on the sides will only contribute to that part of the drag coefficient due to the incident molecules. The exact expression for this part of the coefficient in a particular direction on a convex element of area is

$$dc = \frac{1}{A_{ref}}[(\varepsilon p+\gamma q+\eta r)[\gamma(1+erf(\gamma S)) + \frac{1}{S\sqrt{\pi}} exp(-\gamma^2 S^2)] + \frac{2}{2S^2}(1+erf(\gamma S))]dA \tag{43}$$

where ε, γ, η are the direction cosines between the velocity v_s and local x, y, z axes (y normal to the surface) and p, q, r are the direction cosines between the direction in which the force is desired and the local x, y, z axes. For the force normal to the ends for an element on the side in the end-on orientation, we have $\varepsilon = p = 1$, $\gamma = q = 0$, $\eta = r = 0$ and equation 43 gives

$$dc \simeq \frac{1}{A_{ref}} \frac{1}{S\sqrt{\pi}} \tag{44}$$

If we take the circular cross-section as reference area and sum over the side-area, we see that the drag coefficient of a single e.t. should be increased by an amount given by

$$\Delta C_D = \frac{22.4}{S\sqrt{\pi}} . \tag{45}$$

For a typical speed ratio $S = 7$, equation 45 gives $\Delta C_D = 1.8$. Thus, the appropriate value of the drag coefficient for a single e.t. in the end-on orientation is perhaps 4.0 or 4.1 rather 2.2 or 2.3 if the cross-section is taken as the reference area.

7.2 Formulas for Lifetime Calculations

Here we will develop some simple formulas for the determination of the drag coefficient for various configurations of the assembled e.t.'s which could be of interest. We will assume free-molecular flow to apply.

We consider as a reference a cylindrical body (in the most general geometrical meaning) with the generating axis parallel to the velocity vector, having a cross section area A and a lateral area L (see Figure 8.1). The formula for the drag force is the following:

$$F_D = -(2.2\ A + .0806\ L)\ \rho \frac{v^2}{2} \tag{46}$$

where ρ is the atmospheric density and v is the velocity of the system.

We will now apply this formula to the configuration of e.t.'s assembled as in Figure 8.2. We have

$$A = hD\ , \quad h = 2hD(n-1)(1+D/h) \tag{47}$$

where h is the length and D the diameter of a single tank and n is the number of tanks in the assembly. From equation 46 the acceleration due to atmospheric drag is given by

$$a = F_D/nM = -\rho\frac{v^2}{2}\frac{hD}{M}\left[\frac{2.2}{n} + 0.0806\ \frac{n-1}{n}(1+\frac{D}{h})\right] \tag{48}$$

where M is the mass of one e.t. Equation 48 may also be written as

$$a = - C_D \rho \frac{v^2}{2} \frac{hD}{M} \left[\frac{1}{n} + 0.0366 \frac{n-1}{n}(1+\frac{D}{h})\right] \qquad (48^2)$$

where C_D has the value 2.2 currently used for ordinary satellites. The formula allows an easy evaluation of the dependence of atmospheric drag deceleration on the number of tanks.

We also consider the configuration shown in Figure 8.3. In this case we have

$$a = F_D/(nmM) = - \frac{\rho v^2}{2nmM} \Big[2.2\ [D^2(m-1) + \pi D^2/4] + 0.0806\ [\pi+2(m-1)]\ nDh\Big] \qquad (49)$$

where m and n are the dimensions of the assembly in tanks normal and parallel to the direction of motion. This equation can also be written in the form

$$a = - C_D \rho \frac{v^2}{2} \frac{Dh}{M} \left[(m-1+\pi/4) \frac{D}{nmh} + 0.0366\left[\frac{2(m-1)}{m} + \frac{\pi}{m}\right]\right] \qquad (49^2)$$

which permits comparison with equation 48^2.

In Table 2 and Table 3 we have tabulated the values of the coefficients in parentheses from equations 48^2 and 49^2, respectively.

Table 2

n =	1	2	3	4	5	11	25
	1	0.52	0.36	0.28	0.23	0.13	0.081

Table 3

m\n	1	2	3	4	5	∞
1	0.25	0.186	0.16	0.15	0.14	0.115
2	0.25	0.17	0.15	0.13	0.12	0.094
3	0.25	0.17	0.14	0.13	0.12	0.087
4	0.25	0.17	0.14	0.126	0.117	0.084
∞	0.25	0.16	0.13	0.118	0.109	0.073

We conclude this section by noting that the rate of change of the semi-major axis $\dot{A}$ for an e.t. in a circular orbit can be computed from

$$\dot{A} = - C_D(A/M)\rho a^2 n = - kC_D(A/M)\rho a^{\frac{1}{2}}\ , \qquad (50)$$

where k is the Gaussian gravitational constant for the earth. If A/M is in

$cm^2\ g^{-1}$, ρ in $g\ cm^{-3}$, a in km and $\dot{a}$ in $km\ d^{-1}$ this can be written as

$$\dot{a} = -5.455x10^{12}\ C_D(A/M)\rho a^{\frac{1}{2}}\ . \qquad (50^2)$$

8. POSSIBLE STRATEGIES FOR ASSEMBLING THE SPACE STATION

Let us assume that we want to assemble a space station in an orbit with 28° inclination using a substantial number of the external tanks launched in the period 1985-1990, or some period of the same length a few years later. The first problem is how to control the lifetime of the growing system during its build-up period.

It is important to remember that an e.t., when released, will stabilize in a short time in a gravity gradient controlled attitude with the long axis oriented toward the earth. This corresponds to n = 1 in Table 2 and implies an A/M = 350 m^2/32 ton = 0.11 cm^2/g. The rate of orbital decay in the height range between 300 and 500 km, as computed from equation 50^2, is plotted for this area-to-mass ratio in Figure 9 for low, moderate and high levels of solar activity (exospheric temperatures of 700 K, 1000 K and 1500 K, respectively; densities taken from U.S. Standard Atmosphere Supplements, 1966), taking C_D = 2.2. In addition to the variation with height, the figure reflects the large variation of density with solar activity. This variation amounts to nearly an order of magnitude at 300 km and to nearly two orders of magnitude at 500 km. Its effect on the orbital decay of an e.t. is quite dramatically illustrated in Figure 10, which shows height as a function of time for an object with A/M = 0.11 cm^2/g for two different cases starting from a circular orbit at 500 km. The plotted values were obtained by numerical integration with the actual historical record of the relevant geophysical parameters as input to one of the standard atmospheric models. In one case, the initial epoch was in July 1958, near the maximum of Cycle 19, at what is probably the extreme of high solar activity. The total lifetime in this case was only about 10 months and the decay from 400 km height took less than 2 months. In the second case, the initial epoch was taken 1000 days later, when solar activity was approaching a minimum. The total lifetime in this case was about 6.5 years. The decay from 400 km still took only somewhat less than 6 months, however, as the decay coincided with the rise in solar activity at the beginning of Cycle 20.

It is clear from the above that, while a strategy can probably be developed to cope with moderate levels of solar activity, a really high level of solar activity would make the assembly of the e.t.'s extremely difficult if not impossible. Thus, phasing of the assembly process with respect to the solar cycle is very important. In this connection, we note that the initial "window" suggested above corresponds to the approaching minimum of solar activity.

Consider now the sequence of configurations in Figure 11, which may represent the initial stage of evolution of a space station constructed from the e.t.'s. Let us start with configuration 1 and assume that every two months or so we add an external tank, passing in one year from configuration 1 to configuration 5. If we start at 400 km altitude at a time of low solar activity, the orbit of the first external tank can be seen by integration of equation 50^3 to decay by only 3.9 km in two months. If another tank is added at the end of those two months, the effective A/M will be 0.057 cm^2/g and the orbit will decay by only another 2.2 km in the next two months. Proceeding similarly, at the end of the eighth month we would arrive at configuration 5 with an effective A/M of only 0.025 cm^2/g and a decay rate of only 0.018 km/d at a height of about 391 km. If the tanks were to be delivered at 3-month rather than 2-month intervals, we would arrive at configuration 5 in one year at a height of about 386 km and with a decay rate of only about 0.020 km/d. Figure 12 shows the decay history of the system for the two cases of tank delivery at 2-month and at 3-month intervals.

This strategy for the initial assembly of the tanks doesn't seem to be workable at higher levels of solar activity, however. Even for moderate solar activity, the atmospheric density at 400 km is roughly 6 times greater than it is for low solar activity. Starting at 400 km in this case, the orbit of the first tank would decay by roughly 30 km in the first 2 months and the whole assembly would decay entirely before configuration 5 was reached, even with tank deliveries at 2-month intervals.

This assembly strategy also implies a Shuttle capable of operating in circular orbit at a height of 400 km, while carrying the external tank. Probably this would limit the payload carried for each mission in which an external tank was carried to this orbit.

This payload penalty and the effect of atmospheric drag can both be significantly reduced if a facility for deployment and retrieval of heavy payloads is included on the mission which carries the first external tank into orbit. We will call this element the PMDR: Pallet Mounted Deployer and Retriever. This system has a variety of applications and therefore should not be considered as a tool dedicated only to the assembly of the space station. The PMDR should have a 50 km tether with a breaking limit of 2 tons (assuming a safety factor of 4). The total mass of the tether is estimated to be 2.1 ton; the pallet may weigh a few tons.

Before describing an operational strategy using the PMDR, however, we want to see how the orientation of an assemblage of e.t.'s can be controlled so as to reduce the effect of atmospheric drag. We first note that, with reference to Figure 11, the gravity gradient controlled orientation for 6 or more e.t.'s assembled side-by-side changes from "Type 1" as shown in Figure 8.2 to "Type 2" as shown in Figure 8.3. Thus, as can be seen from Table 2 and Table 3, the natural orientation is always just the reverse of the one that would give the lesser atmospheric drag. In Figure 13, we show how a tethered external mass can be used to stabilize a large assemblage of e.t.'s in the reverse orientation. The configuration of Figure 13 will be stable if the number of e.t.'s is

$$\begin{aligned} n \text{ odd}: \quad & nI_1 + 2MR^2\,[2^2 + 4^2 + 6^2 \ldots + (n-1)^2] < nI_2 + \frac{nMmh^2}{nM+m} \\ n \text{ even}: \quad & nI_1 + 2MR^2\,[1 + 3^2 + 5^2 \ldots + (n-1)^2] < nI_2 + \frac{nMmh^2}{nM+m} \end{aligned} \qquad (51)$$

Assuming $n = 24$, $I_1 = M\ 10$, $I_2 = M \times 50$, $M = 32$ tons, $m = 1$ ton, we have roughly $h > 1.525$ km, which is a reasonably short cable. The tension in the cable is of the order of 1 kg if h is of the order of 2 km. The PMDR could be used as the external mass in this case and could also be used to reverse the orientation of a smaller assemblage as shown for a single e.t. on the left side of Figure 14.

We now consider a possible assembly strategy using the PMDR that would put the e.t.'s into a circular orbit at a height of about 450 km. Note that the atmospheric density at 450 km is only about a third of what it is at 400 km and that, if the tank were stabilized in an end-on orientation, the rate of orbital decay would be such that the strategy would be viable even for moderately high solar activity. The strategy is as follows:

First phase - In this first flight, the Shuttle carries the external tank and the PMDR to a orbit 220 x 417 km. Then we release the external tank from the Shuttle; connect the deployer system with the external tank, and deploy enough of the tether upward to raise the tank 35 km above the center of mass of the system. At the end of the deployment we release the external tank and the PMDR from the Shuttle bay. The center of mass of this system is in a circular orbit at a height of 450 km at the moment of release. At this point, while the Shuttle re-enters, the PMDR is commanded to move toward the external tank thus reducing the A/M ratio of the overall system and stabilizing it by gravity gradient forces. The deployment of the e.t. by the Shuttle is illustrated in Figure 15.

Second phase - On the next flight, the Shuttle again enters almost the same orbit as before (probably with slightly lower apogee). The PMDR is deployed down and captured in the Shuttle bay. The Shuttle then retrieves the first external tank. Next, the second external tank is detached from the Shuttle and connected with the first external tank. The two external tanks are then deployed upward with the PMDR and the system of the two external tanks plus the PMDR is released when the overall system is at apogee in a orbit at almost the same altitude as in the first phase. Now we have two external tanks plus the PMDR in a circular orbit.

Third phase and beyond - The procedure follows the same process as the second phase allowing us to assemble and stabilize any number of external tanks in orbit. The sequence of configurations of the assembled tanks is shown in Figure 16.

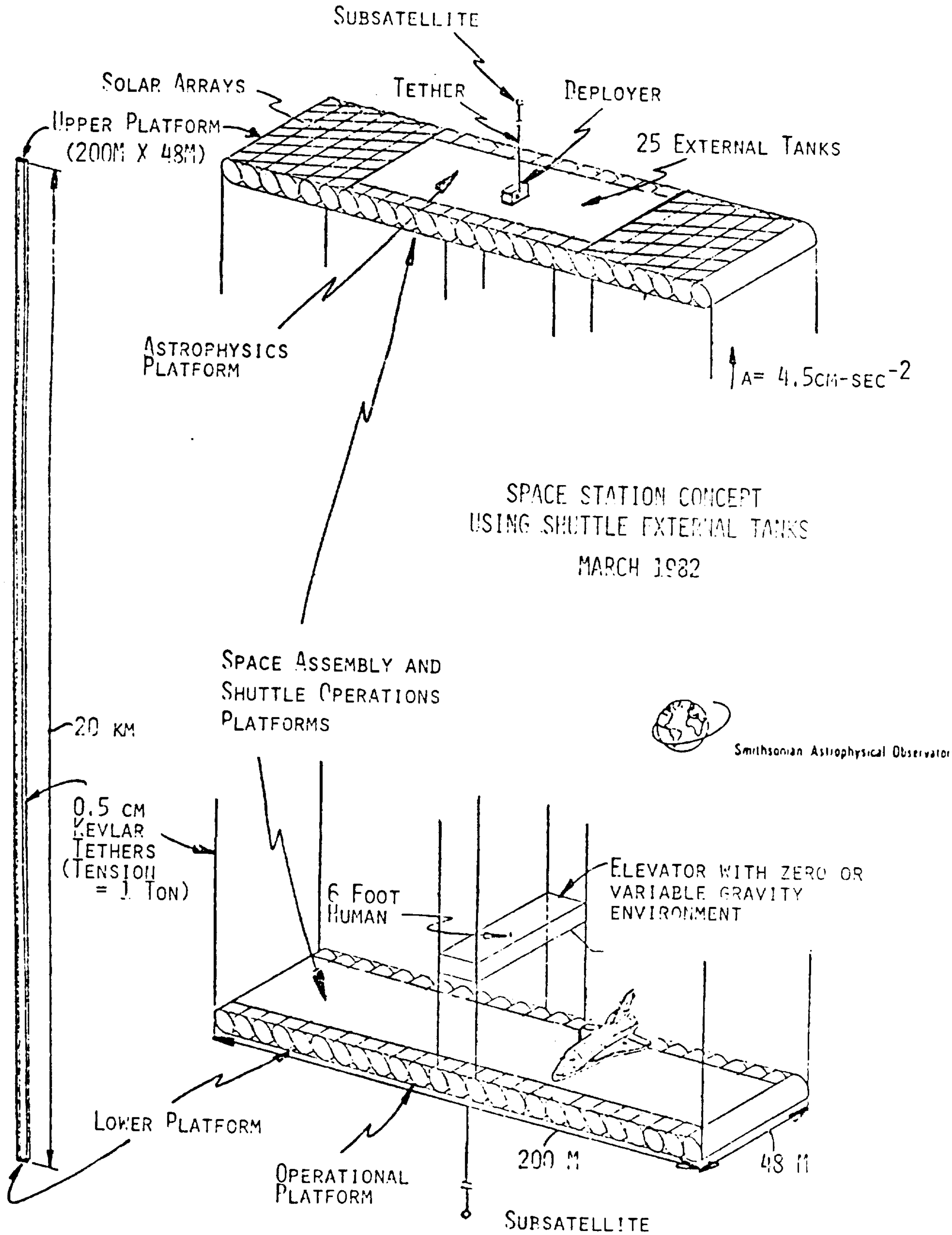

Figure 1. Symmetric Platform.

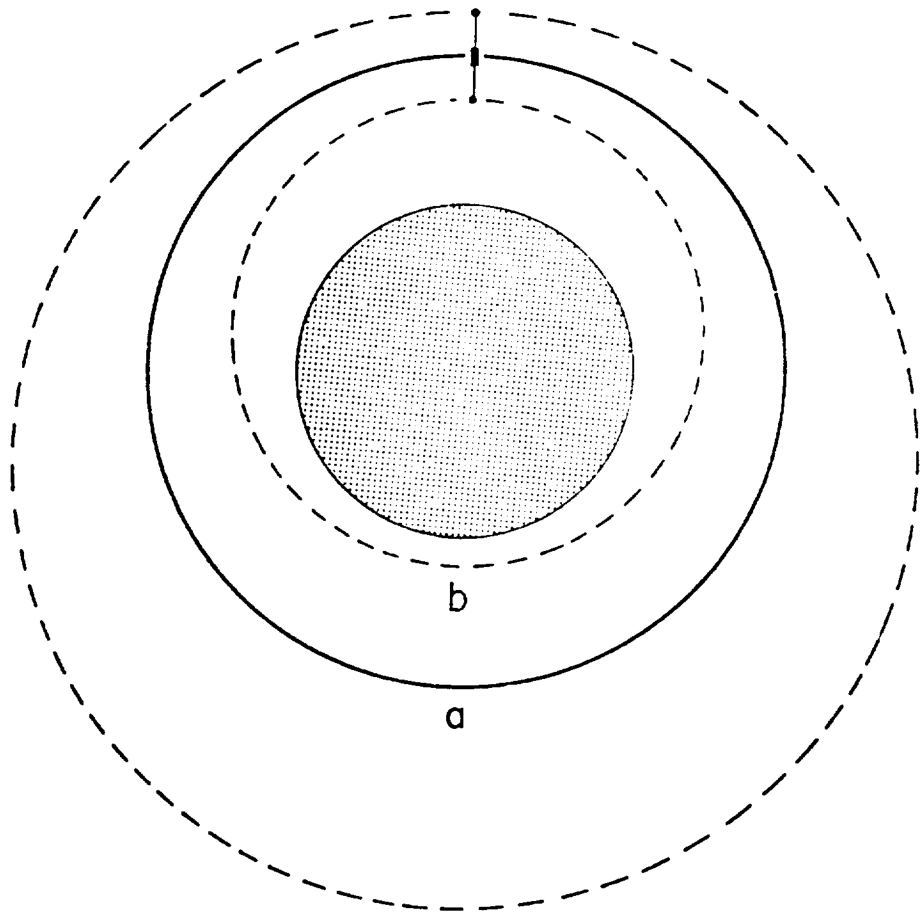

Figure 2. Orbital Relationships in Payload Orbital Transfer

a) Circular orbit of the center of mass G of the platform.

b) Eccentric orbit of a payload released from the lower deck with a deployer. Apogee at point of release, perigee at opposite point of orbit.

c) Eccentric orbit of a payload released from the upper deck with a deployer. Perigee at point of release, apogee at opposite point of orbit.

Notice that (b) may also be the orbit of the Shuttle carrying a payload up or down. Notice also that (c) may be the orbit of a payload captured from a high eccentricity orbit.

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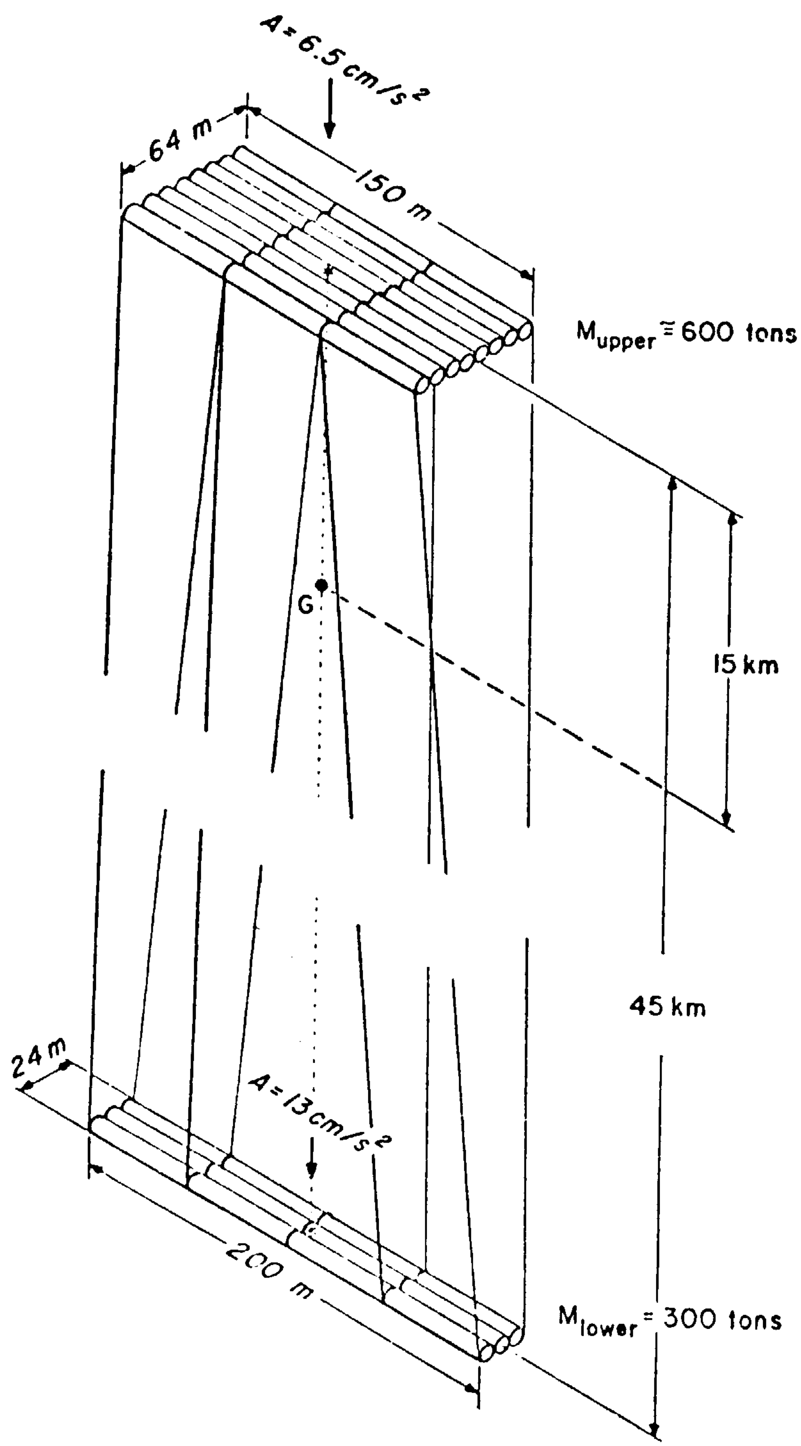

Figure 3. Example of an asymmetric platform. The total number of External Tanks used is 36; 24 of them are assembled to form the upper deck, 12 the lower deck. The two decks are linked by 8 cables, 0.5 cm diameter, of 45 km length. The system in circular orbit at 400-500 km has the mean motion of the center of mass of the system which lays roughly 15 km below the upper deck and 30 km above the lower deck. The total tension is of the order of 5 tons distributed in the 8 cables.

The asymmetric configuration has the following advantages:

a) The upper and lower platforms may be designed so that the atmospheric drag gives a zero torque with respect to G.

b) We have larger acceleration at both the upper and lower levels. In particular, at the lower deck it may be advantageous to have a larger acceleration for simplifying operations there.

c) The lower platform has lower velocity, much lower than the local circular velocity and the Shuttle may dock there with zero relative velocity from an eccentric orbit with much lower perigee.

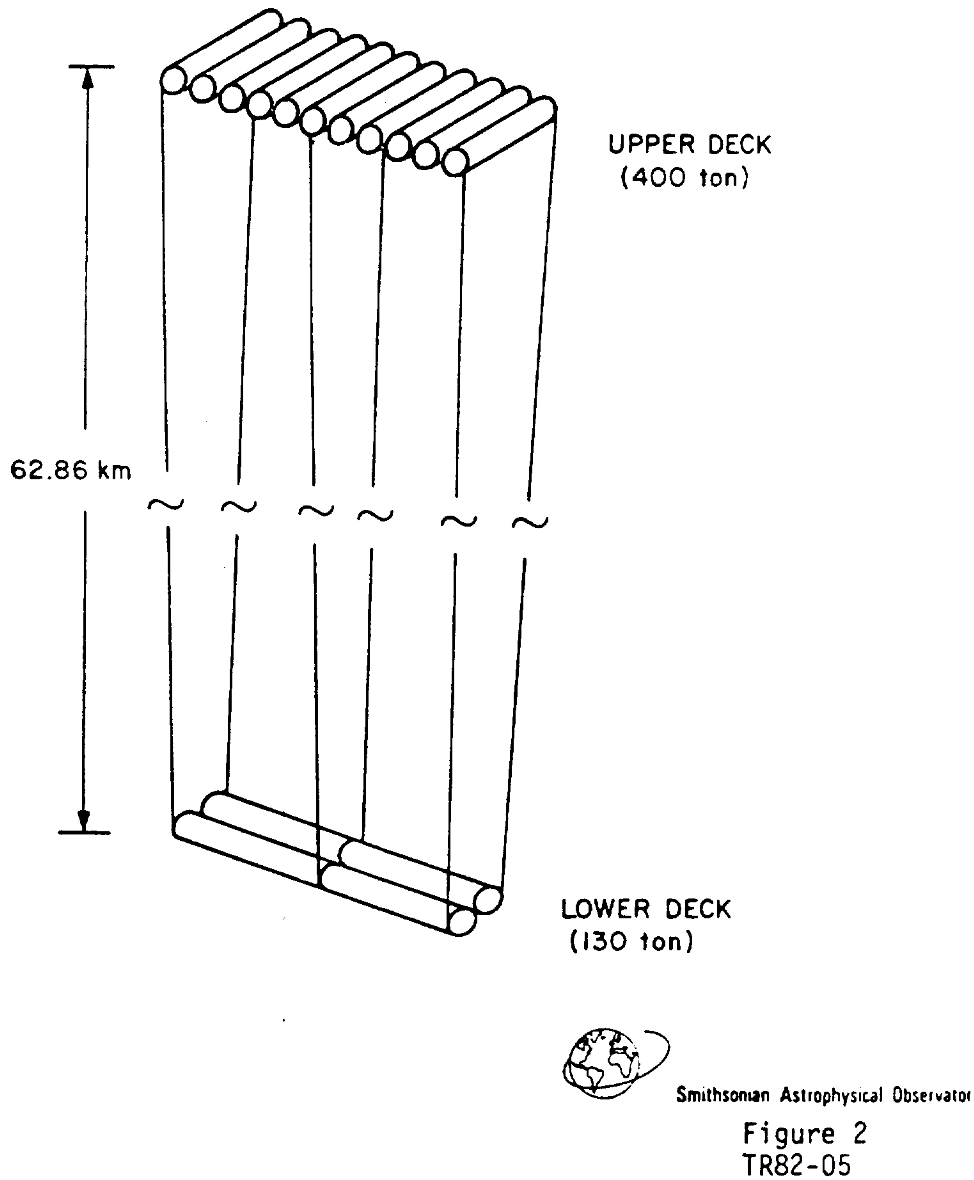

Figure 4. Possible Configuration of the Space Station Using 15 External Tanks.

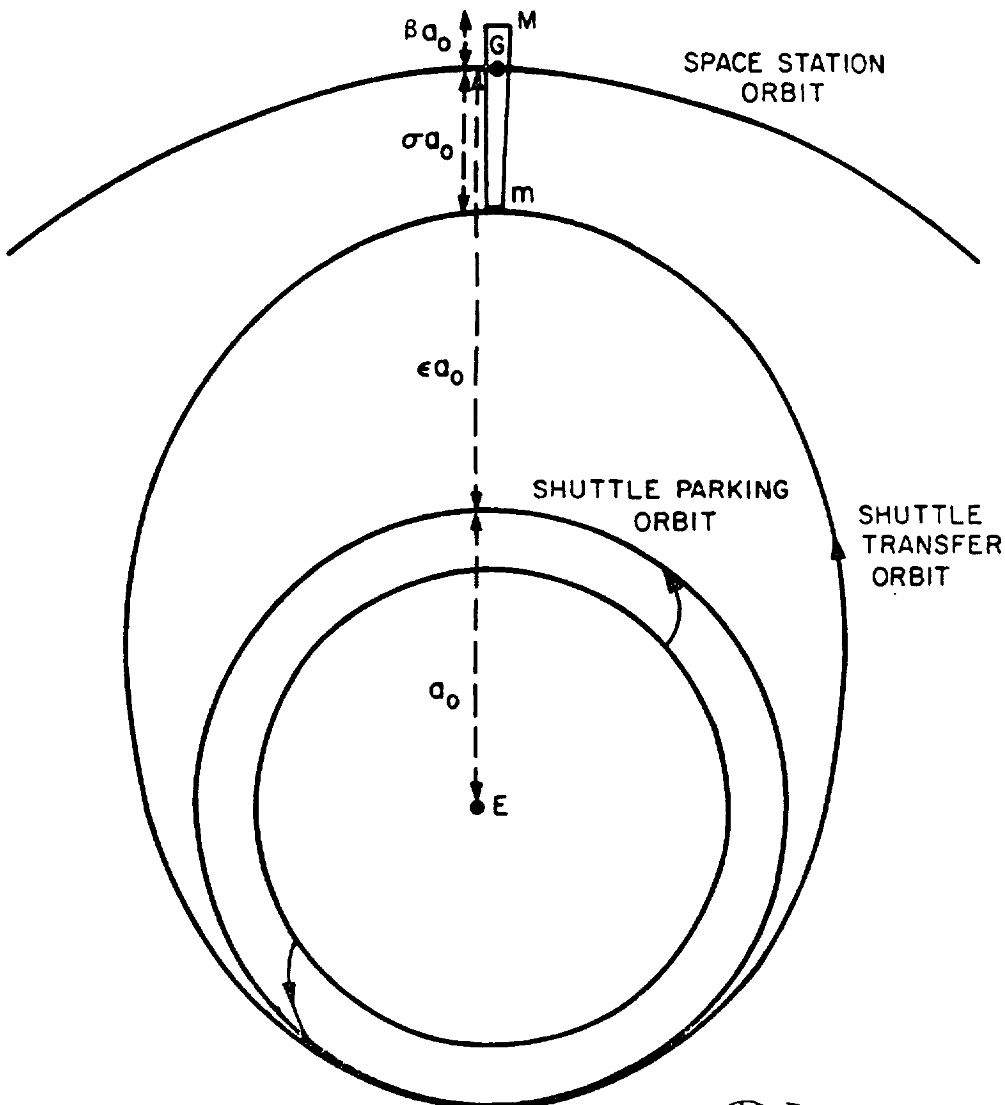

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Figure 1
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Figure 5. Configuration of the Orbital Transportation System from Ground to Space Station, and Related Notations.

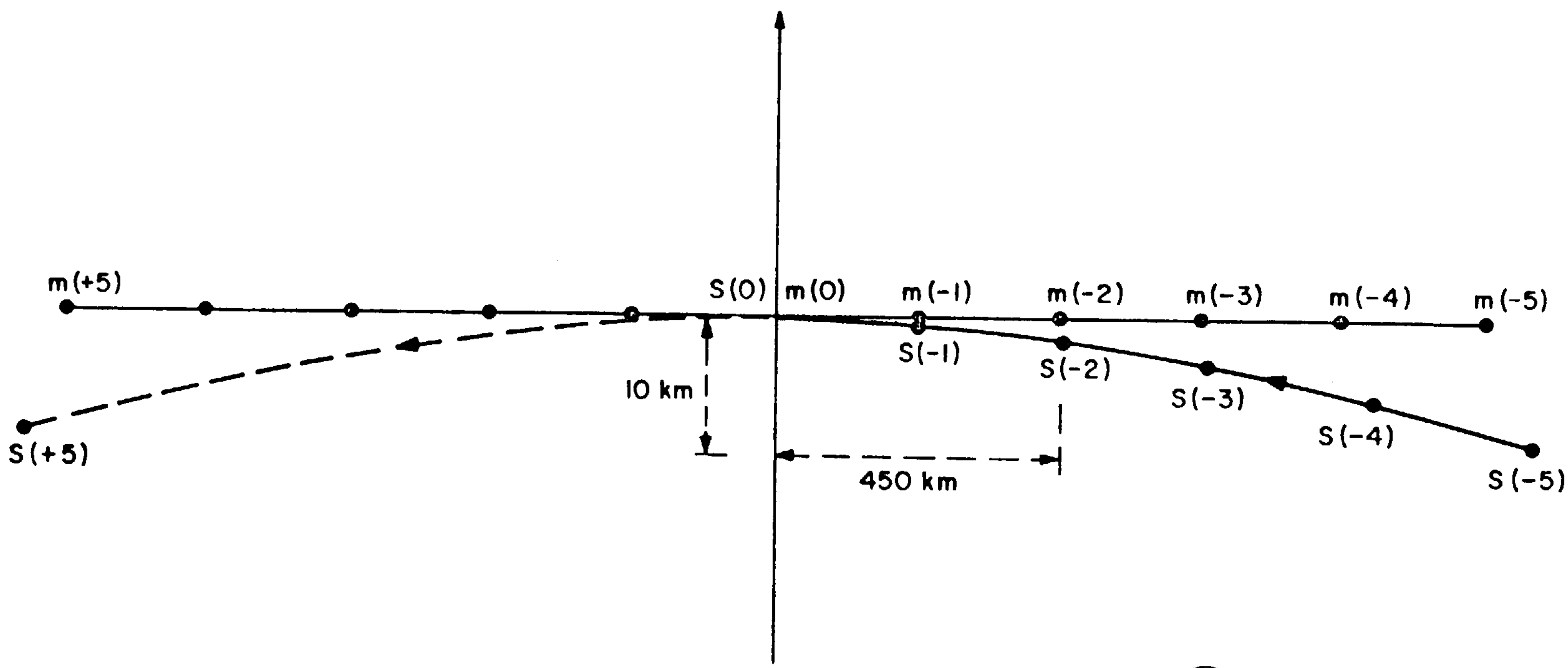

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Figure 3
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Figure 6. Relative Position of the Shuttle with Respect to Lower Deck. The Trajectory of m is Rectified for Reasons of Scale.

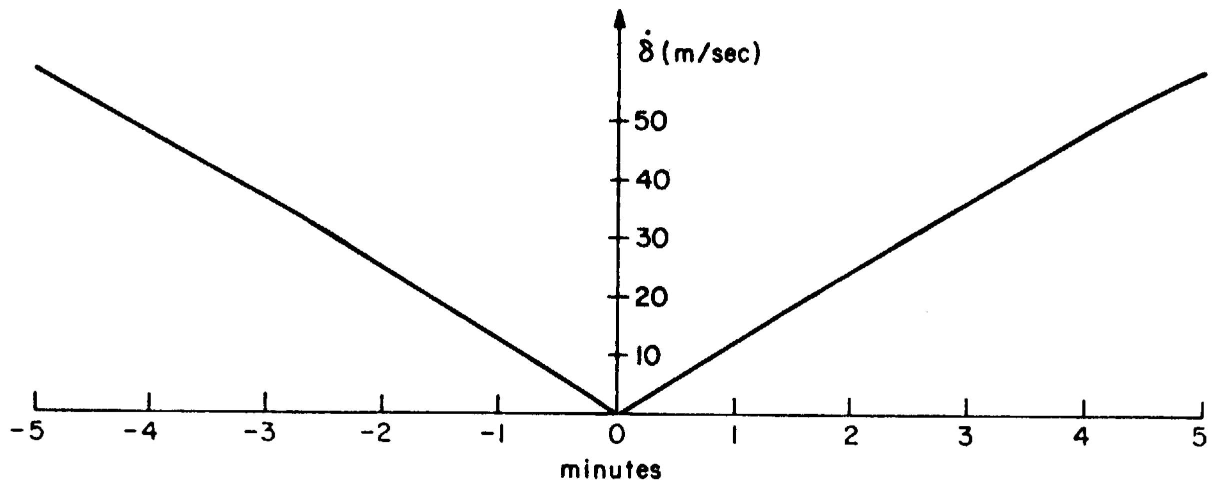

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Figure 4
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Figure 7. Magnitude of the Relative Velocity as a Function of Time, with Origin at the Nominal Docking Point.

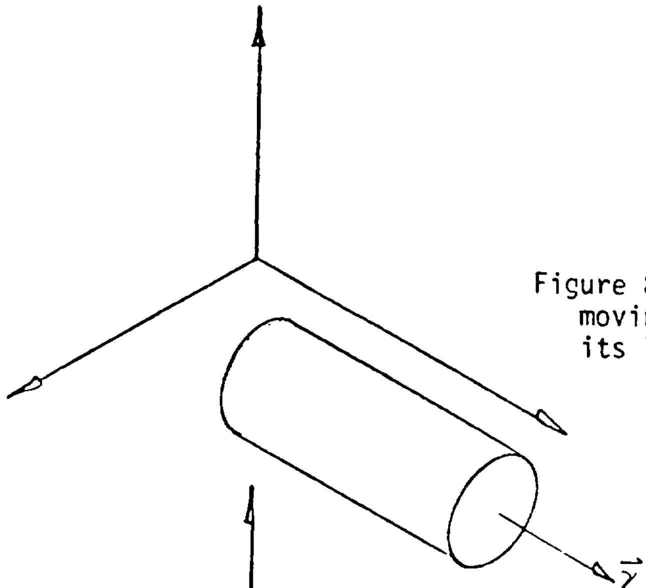


Figure 8.1. A cylindrical body moving in the direction of its long axis.

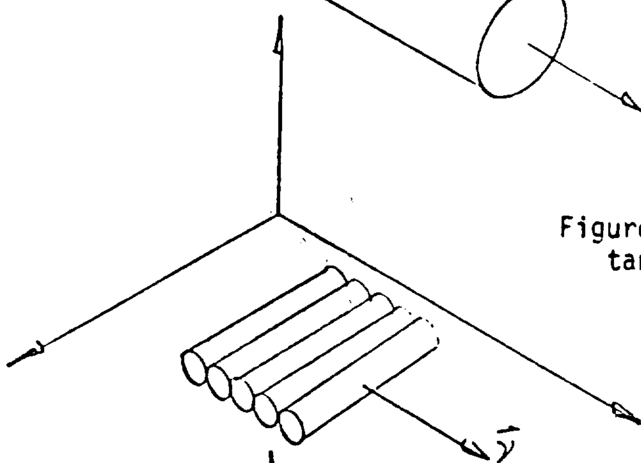


Figure 8.2. A "type 1" external tank assembly.

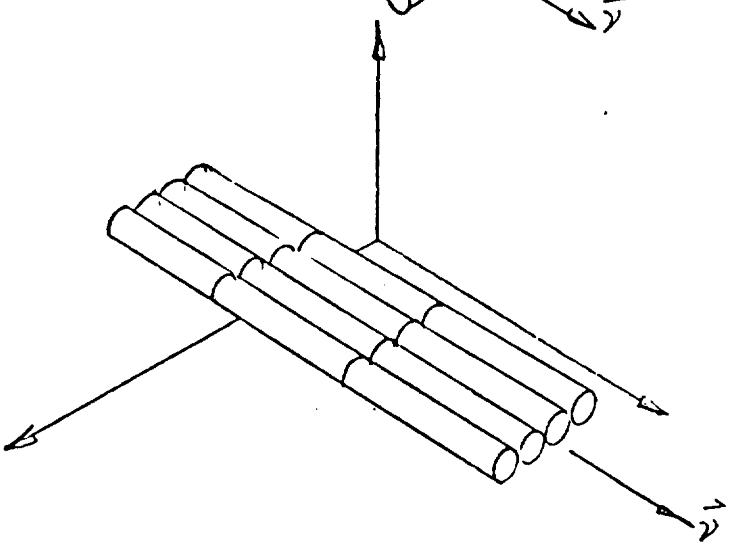
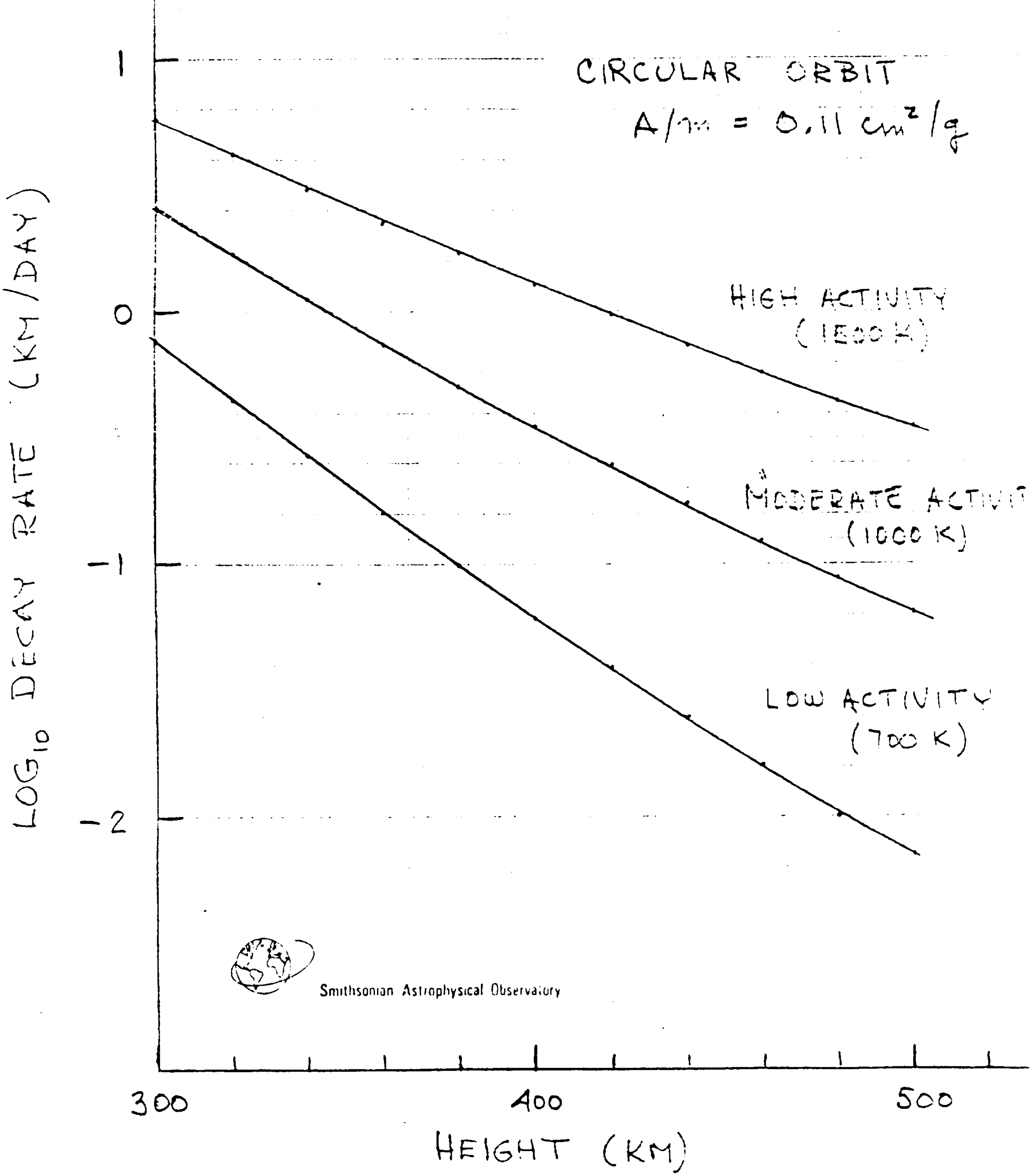


Figure 8.3. A "type 2" external tank assembly.

Figure 8.

Figure 9. Decay rate (logarithmic scale) for a single e.t. as a function of height in the range 300 km - 500 km for different levels of solar activity.



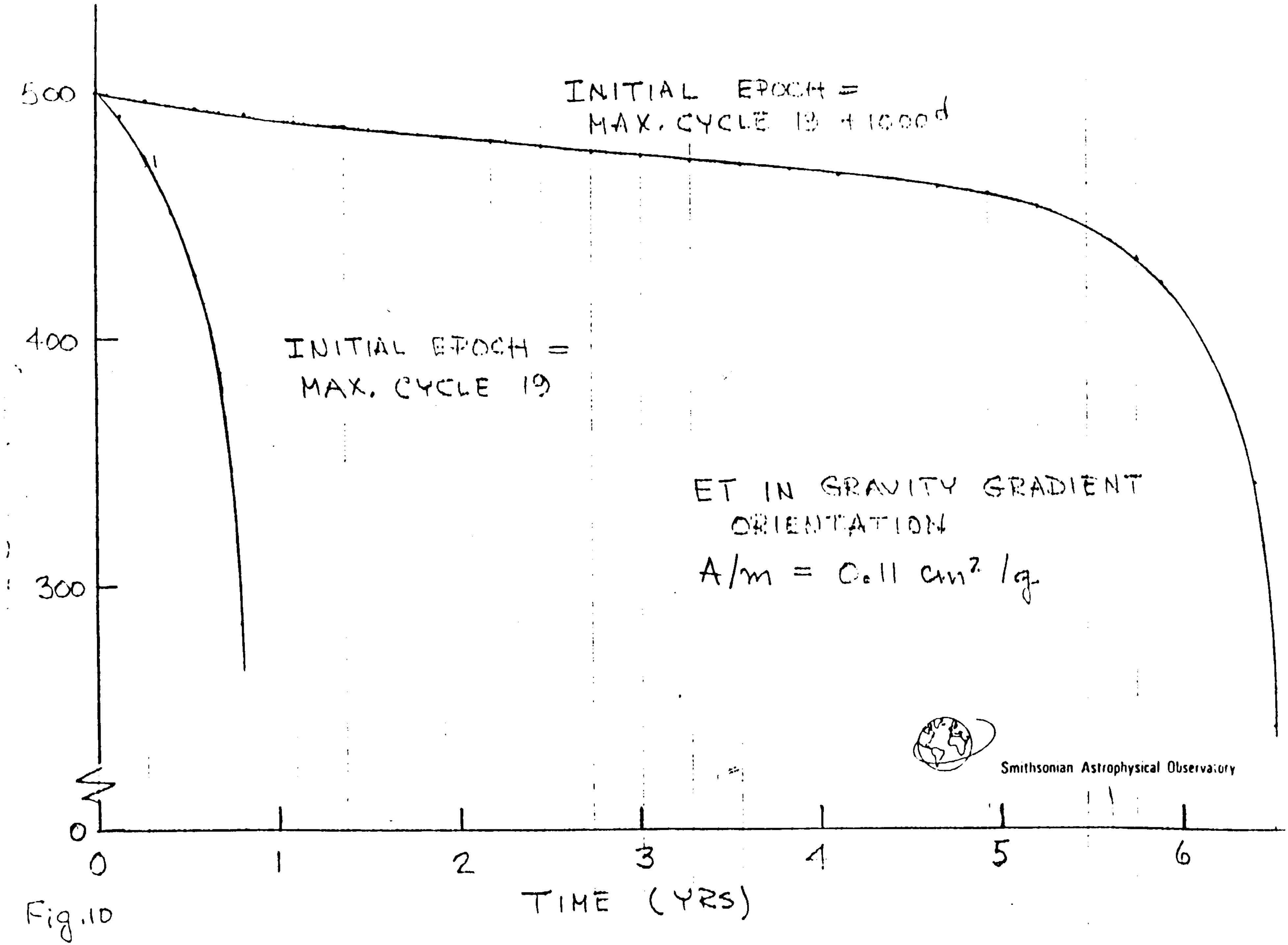


Figure 10. Height as a function of time for a single External Tank starting from two different epochs.

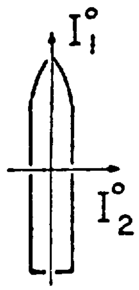
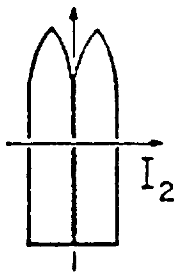
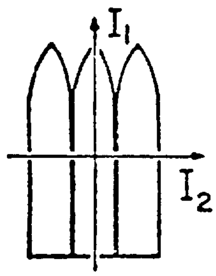
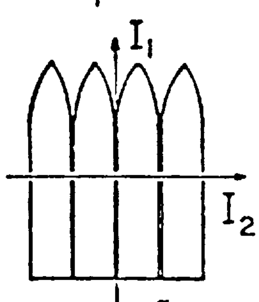
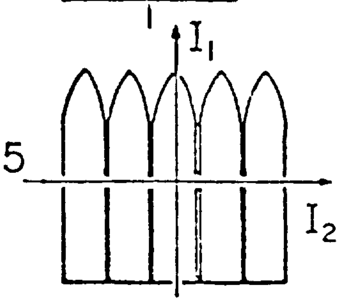
Configuration	A/M (cm^2/gr)	I_1	I_2	I_1/I_2 ($MR^2 = 1.1\ I_1^\circ$)
1 	0.11	I_1°	$11\ I_1^\circ$	0.09
2 	0.057	$2\ I_1^\circ + 2MR^2$	$22\ I_1^\circ$	0.19
3 	0.040	$3\ I_1^\circ + 8MR^2$	$33\ I_1^\circ$	0.357
4 	0.031	$4\ I_1^\circ + 20MR^2$	$44\ I_1^\circ$	0.59
5 	0.025	$5\ I_1^\circ + 40MR^2$	$55\ I_1^\circ$	0.89

Figure 11. Sequence of STS External Tank configurations and related significant dynamic parameter values. These configurations are all gravity-gradient stabilized along the vertical. For a configuration with six tanks, the system is stable with the I_2 axis parallel to the vertical.

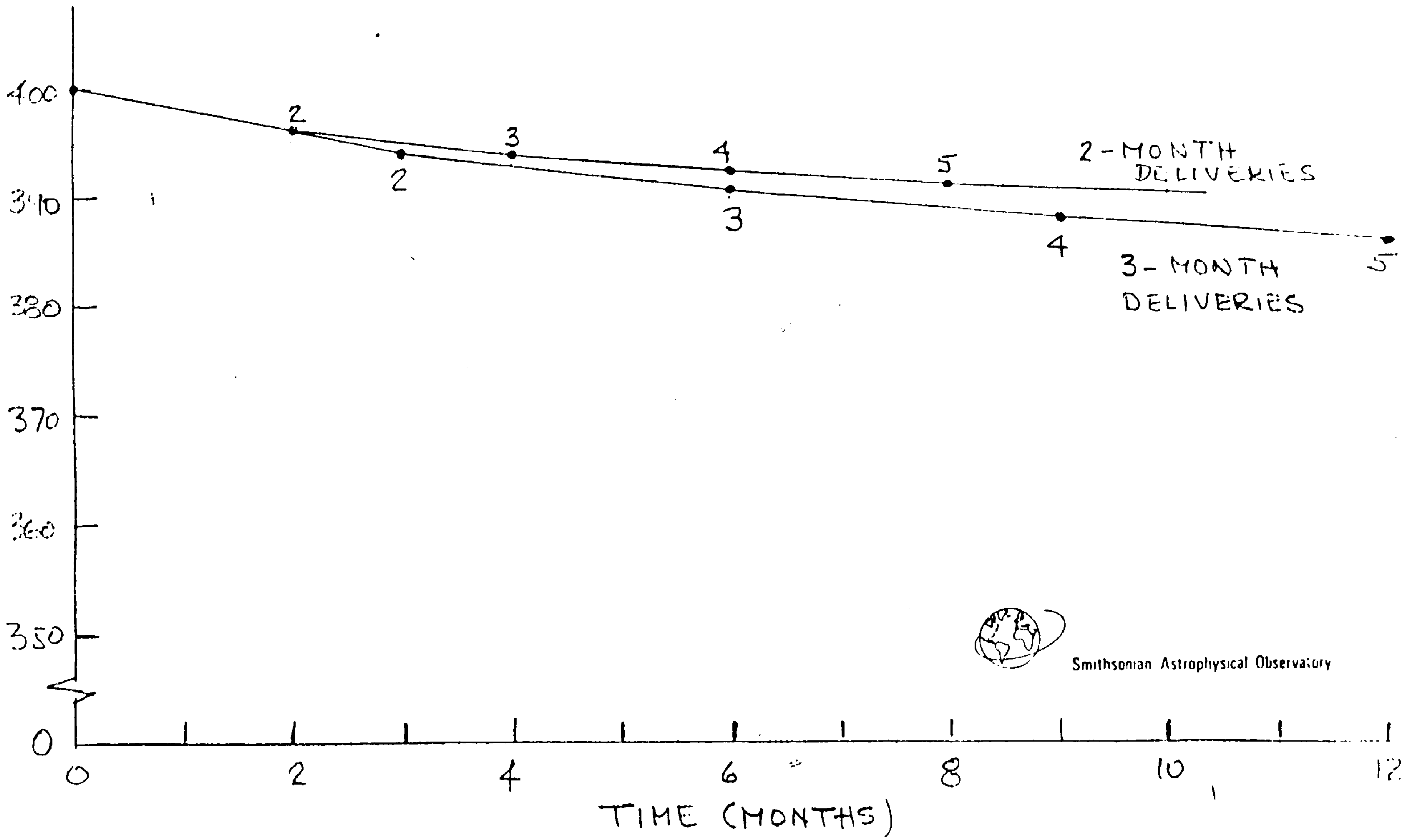


Figure 12. Decay history for assembling a number of External Tanks with two and three month intervals between tank deliveries.

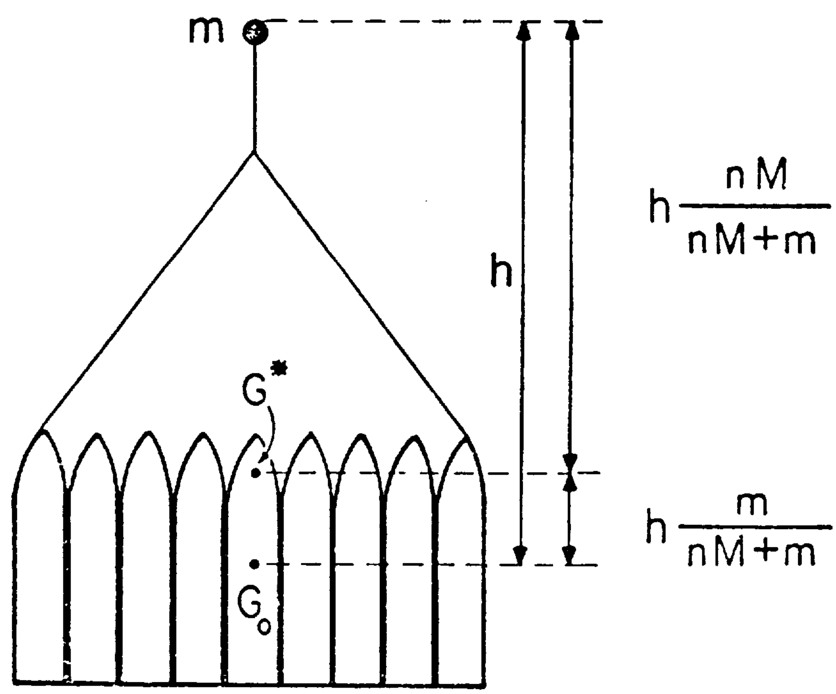


Figure 13. A method for stabilizing n External Tanks for n > 4. For n = 24 h should be of the order of 2 km when m = 1 ton; the tension in the cable is of the order of 1 kg, the corresponding A/M of the system is negligible.

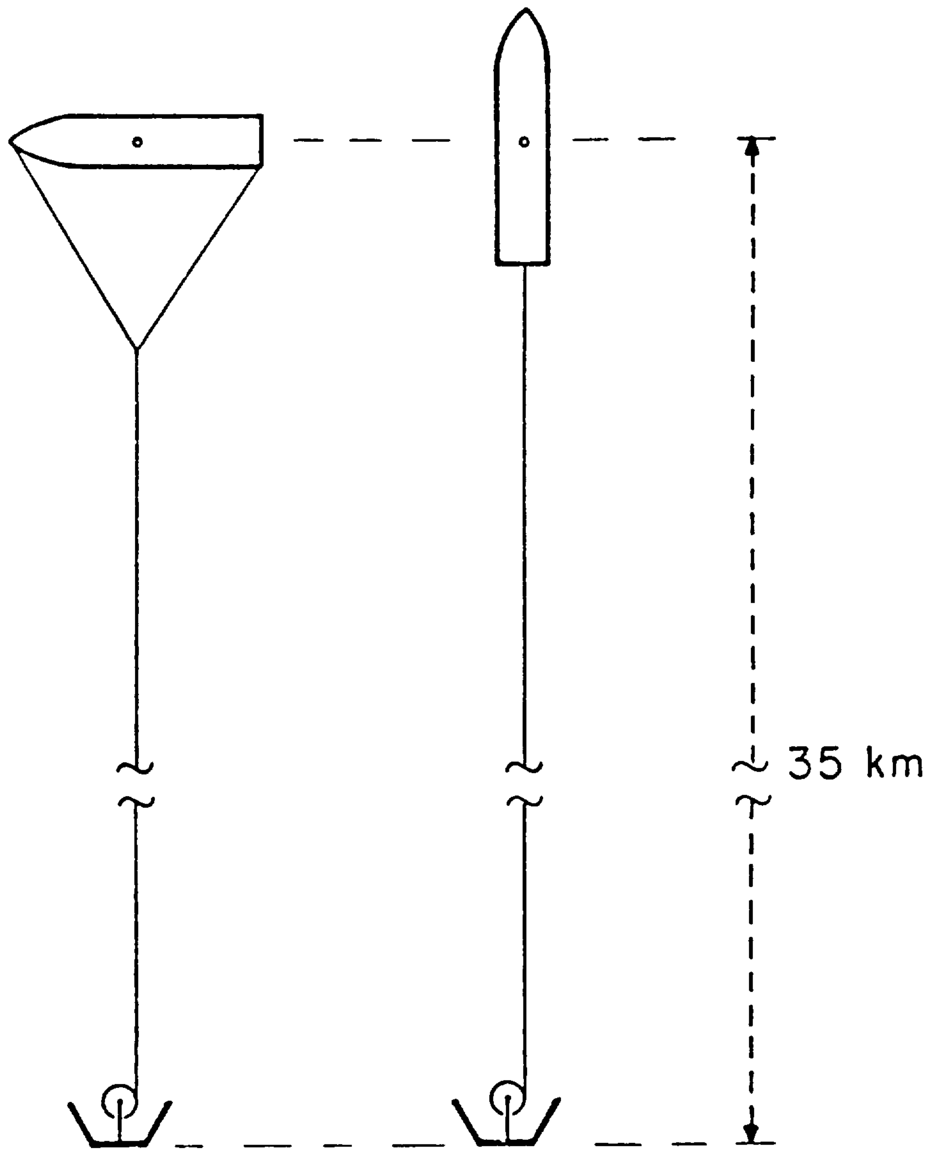


Figure 14. Two possible configurations of an External Tank plus PMDR (Pallet Mounted Deployer-Retriever). The left hand configuration is preferred because it has a lower A/M ratio than the right hand configuration.

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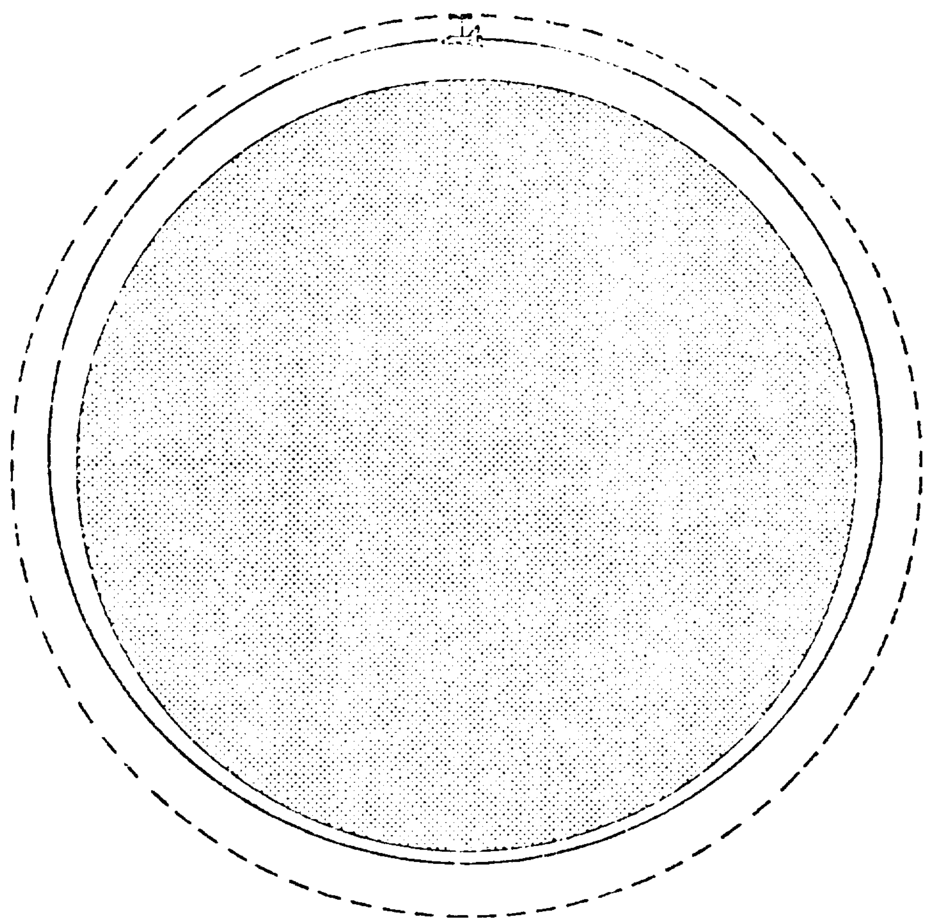

Figure 15. Deployment of an External Tank using a Pallet Mounted Deployer and Retriever. While the Shuttle is at apogee of a 220-417 km eccentric orbit, the release of the External Tank automatically injects the External Tank into a circular orbit 450 km altitude.

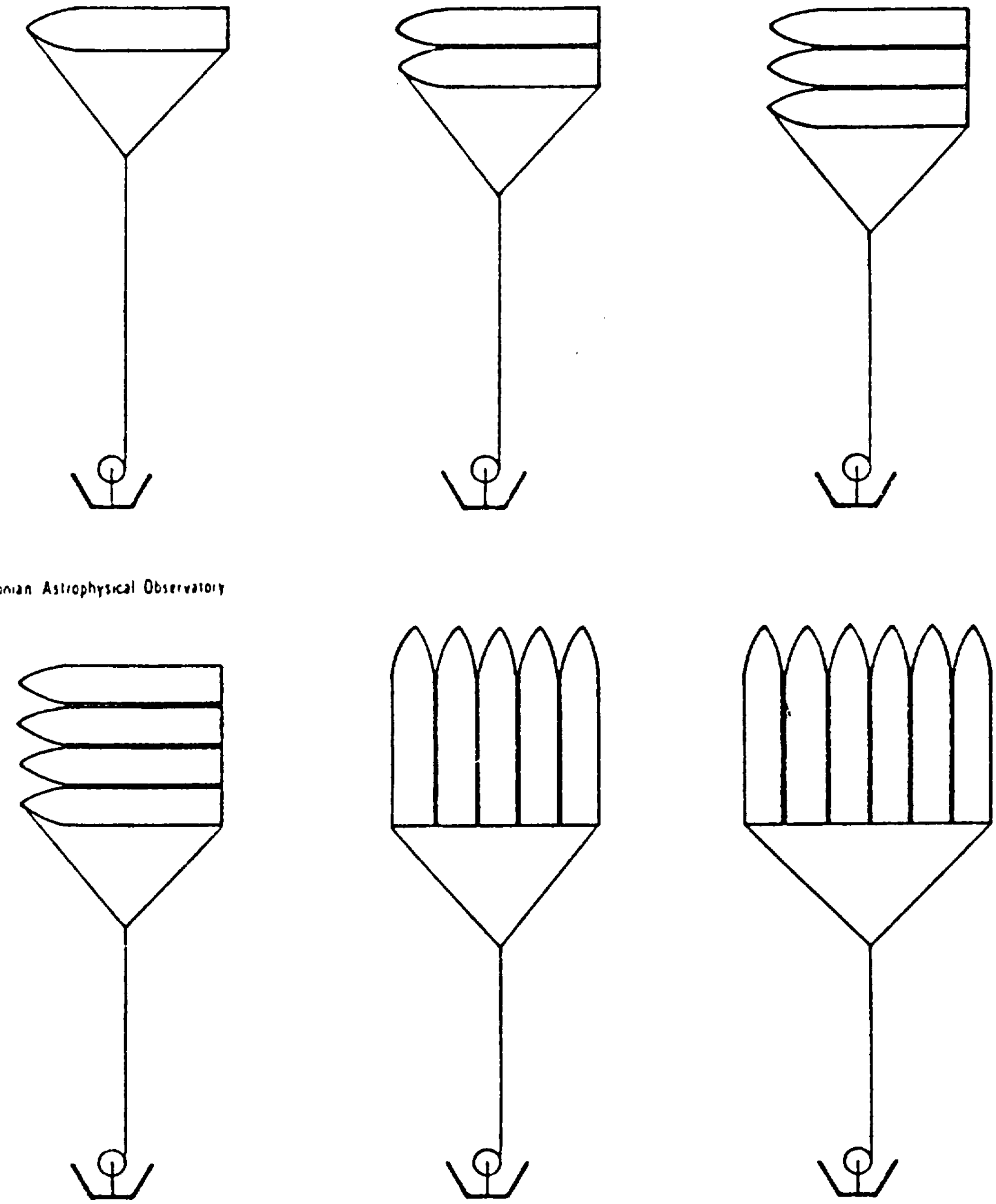

Figure 16. A possible sequence of configurations leading eventually to an assembly of large numbers of External Tanks. Each configuration is chosen to minimize its A/M ratio.